JOC The Journal of Organic Chemistry

Article

Cite This: J. Org. Chem. 2018, 83, 2647−2659

pubs.acs.org/joc

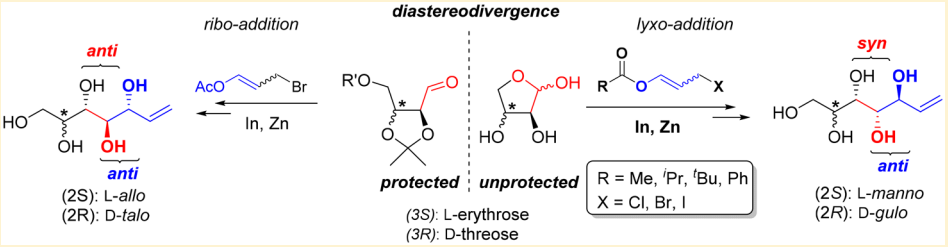
Indium- and Zinc-Mediated Acyloxyallylation of Protected and Unprotected Aldotetroses—Revealing a Pronounced Diastereodivergence and a Fundamental Difference in the Performance of the Mediating Metal

Markus Draskovits,[†] Christian Stanetty,*[,†] Ian R. Baxendale,[‡] and Marko D. Mihovilovic[†]

[†]Institute of Applied Synthetic Chemistry, TU Wien, Getreidemarkt 9, 1060 Vienna Austria

[‡]Department of Chemistry, Durham University, South Road, Durham, DH1 3LE, United Kingdom

Supporting Information



ABSTRACT: The acyloxyallylation of unprotected aldoses was first demonstrated more than a decade ago as a potentially elegant two-carbon homologation of reducing sugars (upon ozonolysis); however, its application in real case syntheses remained scarce. Following up on such a successful showcase and to answer several pending questions about this attractive transformation, we engaged in an in depth methodological reinvestigation. The epimeric tetroses L-erythrose and D-threose in unprotected and protected form were successfully applied to the indium and also zinc-mediated acyloxyallylation, with the latter being a first for an unprotected sugar. The investigation largely benefited from the choice of these more exotic starting materials as it allowed unambiguous identification/quantification of the hexose-products which are available as authentic reference materials. The observed diastereoselectivities indicate a strong substrate control (stereochemistry at *O*2), and the influence of the reagent's structure on the selectivity was investigated in great detail. A strong facial diastereodivergence between related protected and unprotected structures was demonstrated and an unexpected, pronounced principle difference in performance between indium and zinc was revealed.

INTRODUCTION

Carbohydrates are regularly referred to as an important part of Natures chiral pool. However, commercial or facile availability at desirably low cost or effort is in fact limited to only selected representatives of this substance family,[1,2] resulting in two undesirable consequences: First, the use of carbohydrates as chiral starting materials remains often limited to a subset of "common" sugars, and second, methodology development is usually only demonstrated on this same set of abundant derivatives, creating a reinforcing cycle: The use of more exotic sugar building blocks is discouraged by the lack of positive literature precedence. Approaches to extend the range of sugars are being targeted by biotechnology[3] as well as efforts in the field of *de novo* syntheses;[4−6] however, the challenge of mastering the stereoselective modification of one or more centers of an otherwise readily available chiral scaffold is certainly an attractive complementary endeavor. Our current report outlines the potential value of including currently less abundant sugars into a methodological study and in parallel serves our ultimate motivation to increasing the platform of readily available parent sugars for the carbohydrate community and beyond.

In this context, the indium-mediated acyloxyallylation (IMA) of unprotected aldoses with halopropenyl esters as reactants presents great potential as an elegant two-carbon homologation of reducing sugars (upon facile loss of ester protection and subsequent ozonolysis). The use of IMA is a particularly practical approach as the indium (and analogous zinc) organometallics can be formed and reacted under Barbier-type-conditions. Of note the observed selectivities have been shown to be independent of the (*E*/*Z*)-configuration of the reagents and a wide range of reaction conditions are tolerated including protic solvents (alcohols, aqueous solutions) and ambient temperatures.[7−10] This inherent compatibility with unprotected sugars highlights this method from other homologation methods (in particular by two carbons) including alternative α-hydroxyallylations (based on Li, B, Ti, Al, Cr, Zr) which generally require low temperatures and/or anhydrous conditions.[7,11,12] In an initial proof of concept study, standard D-pentoses and D-hexoses were studied as starting materials and the formation of only two out of four

Received: December 4, 2017
Published: January 25, 2018

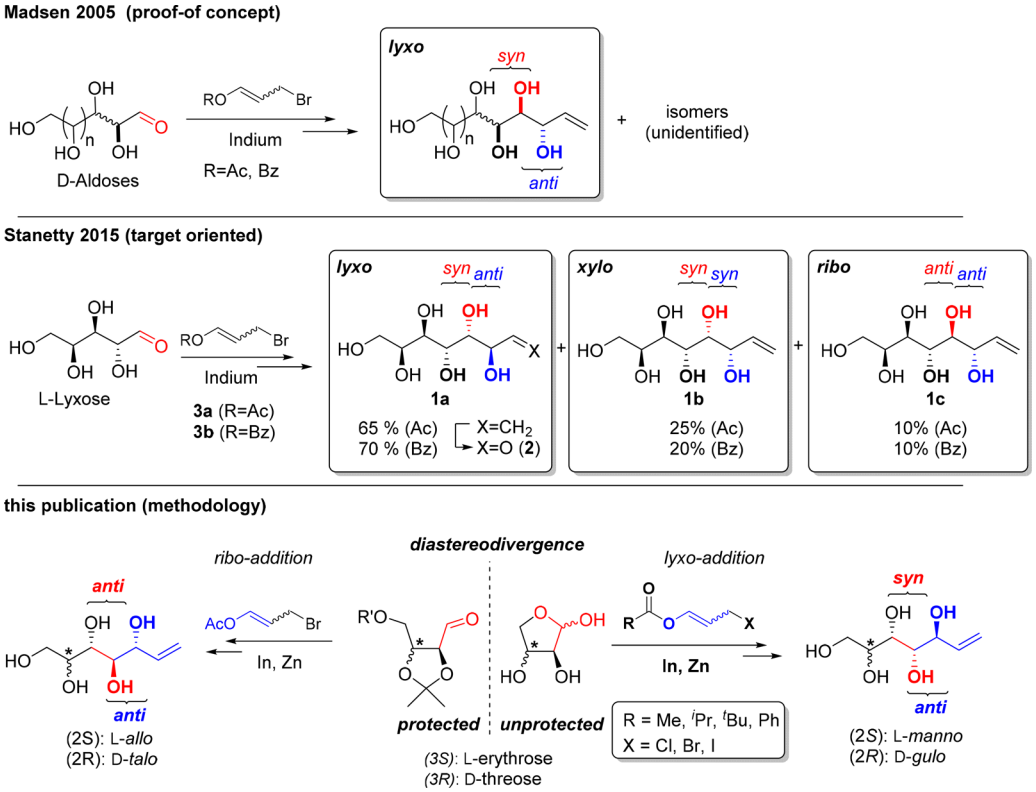


Figure 1. Progress of the state of knowledge of the indium- (and zinc-) mediated acyloxyallylation of aldoses. Reagent (blue) and sugar-derived (red) new stereocenters and partial structures are color-coded.

possible isomers was reported, with moderate to good selectivity for the main product.[13] Only the main products were isolated and identified which exhibited consistently the same relative stereochemistry, namely a *lyxo*-configuration. This configuration represents an *anti*-orientation of the two new stereocenters formed, in a *syn*-fashion with respect to the α-position of the carbonyl moiety in the starting material (Figure 1, top). While the *anti*-addition was in line with the established model for the acyloxyallylations of achiral aldehydes,[9] the facial selectivity (*syn*) in respect to the addition to the carbonyl seems specific to sugars as starting materials. The other isomers were not isolated or identified. Therefore, although widely acknowledged in the literature, this chemistry was never fully explored or exploited.

Recently, we developed a large-scale concise synthesis of the important bacterial sugar L-*glycero*-D-*manno* heptose **2** starting from L-lyxose, featuring a practical preparative indium-mediated acetoxyallylation protocol toward the highly crystalline *manno*-configured enitol **1a** (*lyxo*-type addition) as the key synthetic step.[14] En route, we additionally isolated two further isomers which were identified as the *gluco*- and *allo*-configuration (**1b**, **1c**), derived from *xylo*- and *ribo*-type addition, respectively (Figure 1, middle). In contrast to the original paper (D-lyxose)[13] we observed a significantly less pronounced selectivity for the main isomer and also less of an enhancement when replacing bromopropenyl acetate (**1a**/**1b**/**1c** = 65:25:10) with the corresponding benzoate (**1a**/**1b**/**1c** = 70:20:10). Success in this case study was ultimately derived from the beneficial physical properties of enitol **1a** in its downstream processing. The observed ratios imply a high facial selectivity for the attack of the indium organyl from the *si*-face of the carbonyl (90% for the two main products), with a moderate *anti*-selectivity (**1a**/**1b** ~ 2:1 up to 3.5:1) in the addition step (see Figure 2 for the separate consideration of the two types of selectivity). To the best of our knowledge, this constitutes the first complete set of data describing the outcome of an indium-mediated acyloxyallylation in a complex setting that employing sugars as starting materials constitute. Building upon the knowledge generated, we have decided to expand our efforts into a methodological study to address several open questions in this attractive transformation.

Setting up our methodological survey. To cope with the inherent difficulty of structural analysis of unknown carbohydrate structures as well as the reliable quantification of (isomeric) mixtures thereof, we chose the tetroses L-erythrose and D-threose as substrates for our survey. These species represent two different relative stereochemical configurations (*erythro, threo*) next to the reactive carbonyl center, and with hexoses being the final elongation products (upon ozonolysis), unambiguous identification of all potential products can be guaranteed by comparison with authentic reference materials.

The first question we wished to investigate was whether the product distribution, revealed in our case study, was general and if the moderate selectivity in the addition step could be improved upon via optimization of the reagent. Furthermore, according to the reported literature as well as our own experience, replacement of indium with cheaper zinc was unsuccessful in the acyloxyallylation of aldoses while it gave comparable results with standard aldehydes, a result not explained so far.[8,9] Thus, we set out to better understand the particular challenge of employing zinc in the case of carbohydrate starting materials (Figure 1, bottom right). We also decided to evaluate the corresponding 2*O*,3*O*-isopropylidene protected derivatives in our survey, expecting to observe facial diastereodivergence, yielding the *anti*/*anti*-products (*ribo*-type addition) (Figure 1, bottom left). Precedence for such an inversion of selectivity can be found for example with Garner's aldehyde, one of the few transformations of chiral starting materials with bromopropenyl

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

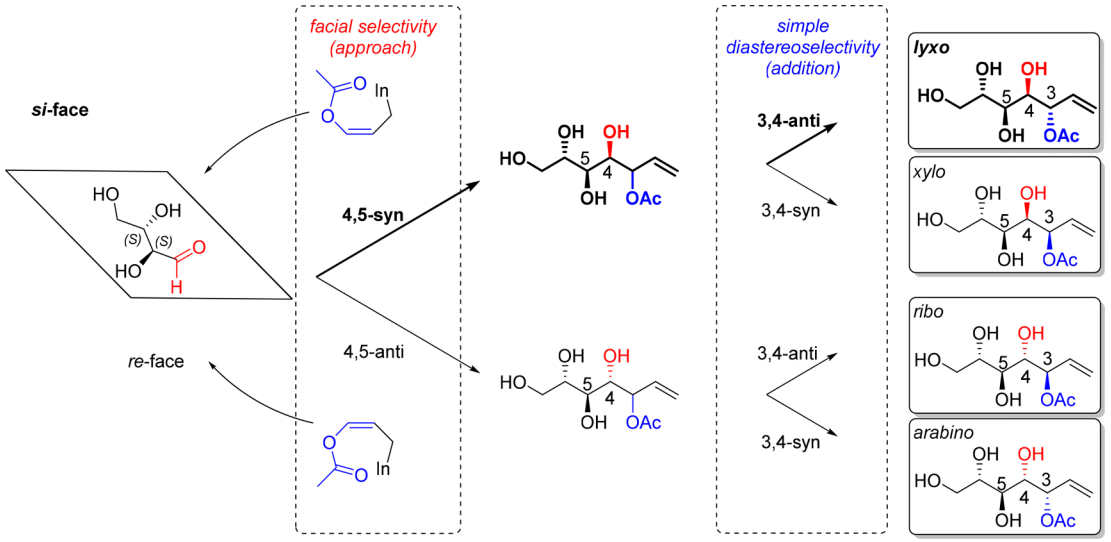
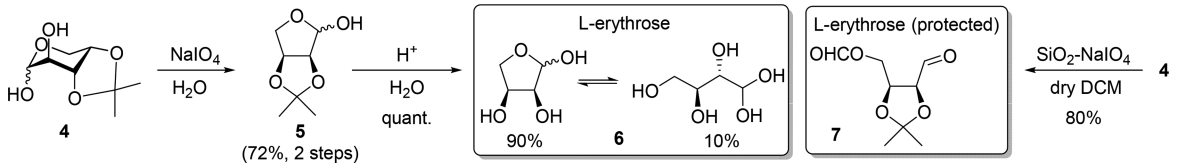


Figure 2. Hypothetical separation of the two types of selectivities observed in the acyloxyallylation of chiral substrates with color-coding for substrate (red) and reagent (blue) derived stereocenters and the path to the observed main product in bold.

Scheme 1. Synthesis of Unprotected (6) and Protected L-Erythrose Sugar Aldehyde 7



esters.[8,15,16] A related facial diastereodivergence was also reported in the simple allylation (only one new stereocenter) of protected and unprotected sugar derivatives[17,18] and the 1,2-addition of 3-bromomethyl-5*H*-furan-2-one to α-chiral aldehydes under the mediation of indium.[19]

For the sake of clarity, the overall process of the addition is hypothetically separated into the approach of the indium organyl onto the carbonyl, related to the facial selectivity (carbonyl), and the actual addition step to the carbonyl, related to the simple diastereoselectivity in the formation of the two new stereocenters (Figure 2).

RESULTS AND DISCUSSION

Acetyloxyallylation of protected and unprotected L-erythrose. We started our investigation with the *erythro*-series. We first synthesized L-erythrose (available but at high prices) from cheap L-arabinose by 3*O*/4*O*-isopropylidene protection (**4**), oxidative cleavage with $NaIO_4$ (**5**),[20] and subsequent acidic hydrolysis to furnish **6**. It is noteworthy that a high degree of the open chain form is present in solutions of **6** (~10% as hydrate according to ^{1}H NMR in D_2O), which is of importance in the later discussion. Alternative treatment of **4** with silica supported $NaIO_4$[21] under nonaqueous conditions furnished protected L-erythrose sugar aldehyde **7** species, a more reactive version of **5** (Scheme 1).

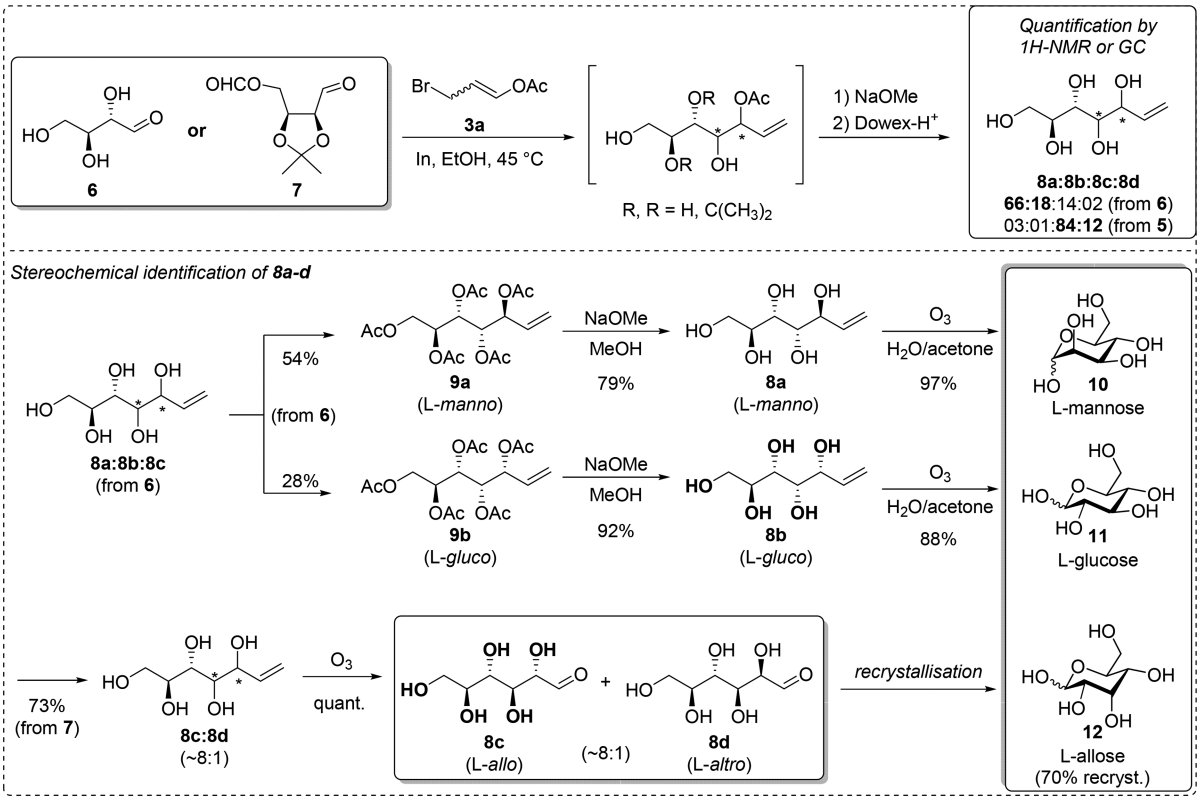
When L-erythrose **6** and bromopropenyl acetate **3a**[9] were subjected to the standard reaction conditions as applied in our preliminary case study (EtOH, indium, 45 °C, 10 min), rapid and full conversion was observed, delivering a mixture of three isomeric enitols (**8a**/**8b**/**8c** = 66:18:14) upon deacetylation. The two major isomers (**8a, 8b**) were obtained in pure form via their peracetates (**9a, 9b**) and were subjected to a modern ozonolysis protocol[22] adopted by us for polar compounds[14] toward the corresponding sugars L-mannose **10** and L-glucose **11** (Scheme 2, middle). Their structures were unambiguously proven by comparison (^{1}H, ^{13}C NMR) to authentic samples (D-hexoses), thus confirming the expected additions (*lyxo*, *xylo*) as predicted from our case study. The stereochemistry of the third compound **8c** was elucidated to be the *allo* (*anti*/*anti*), upon isolation from the analogous experiments with sugar aldehyde **7**, in which **8c** was formed as the major isomer accompanied by the *altro*-isomer **8d** (**8c**/**8d** = 84:12). Ozonolysis of the crude *allo*-enitol (**8c**/**8d**) allowed the isolation of pure L-allose **12** achieved by recrystallization and identification of both sugars (L-altrose **13** in mother liquor) again by comparison with authentic samples (Scheme 2, bottom). All attempts to achieve analogous conversion of **5** (as a simpler version of **7**) under several conditions in different solvents remained unsuccessful, which is attributed to the high stability of the bicyclic system in lactol **5** resulting in low formation of the required open chain form. Quantification of isomers **8a**–**d** was consistently performed either by ^{1}H NMR (diagnostic allylic signals of processed mixtures) or more conveniently by GC-analysis of crude mixtures upon per-OTMS silylation.[23]

In summary a high degree of facial diastereodivergence was observed with **6** and **7**, respectively. While the facial (carbonyl) selectivity was high (85–95%) in both cases, the diastereoselectivity in the addition step was high (7:1) in the protected case (**7**) but only moderate for the acyloxyallylation of the unprotected L-erythrose (**5**). The ratio found (**8a**/**8b**/**8c** = 66:18:14) in the latter case is in line with the results of our previous case study, both with respect to the newly formed stereochemical constitution in the products (*lyxo*, *xylo*, *ribo*) as well as the ratios between them.

The facial selectivity for the *si*-face in the case of the unprotected sugars can be rationalized by a Cram-chelate model

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647–2659

Scheme 2. Facial Diastereodivergence in the Indium Mediated Addition of 3a to Unprotected (6) and Protected L-Erythrose (7)



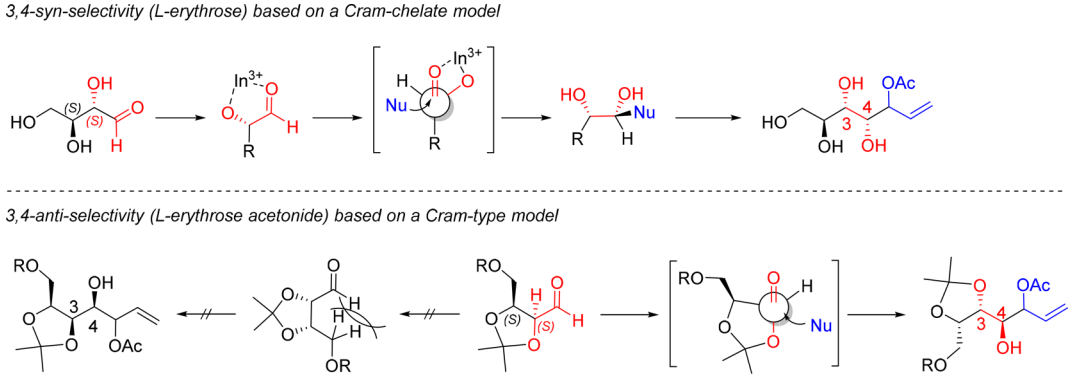


Figure 3. Rationale for the facial selectivity in the acyloxyallylation relating to the dependence of O2/O3-isopropylidene protection.

while a Cram-type model (with the *O2*-oxygen in the anti-periplanar position to the carbonyl) predicts the diastereoselectivity for the protected case (Figure 3, bottom).[17] The *anti*-selectivity in the addition step to the carbonyl is in line with the mechanistic model established for the acyloxyallylation of achiral aliphatic aldehydes by Lombardo and Trombini (*vide infra*).[9]

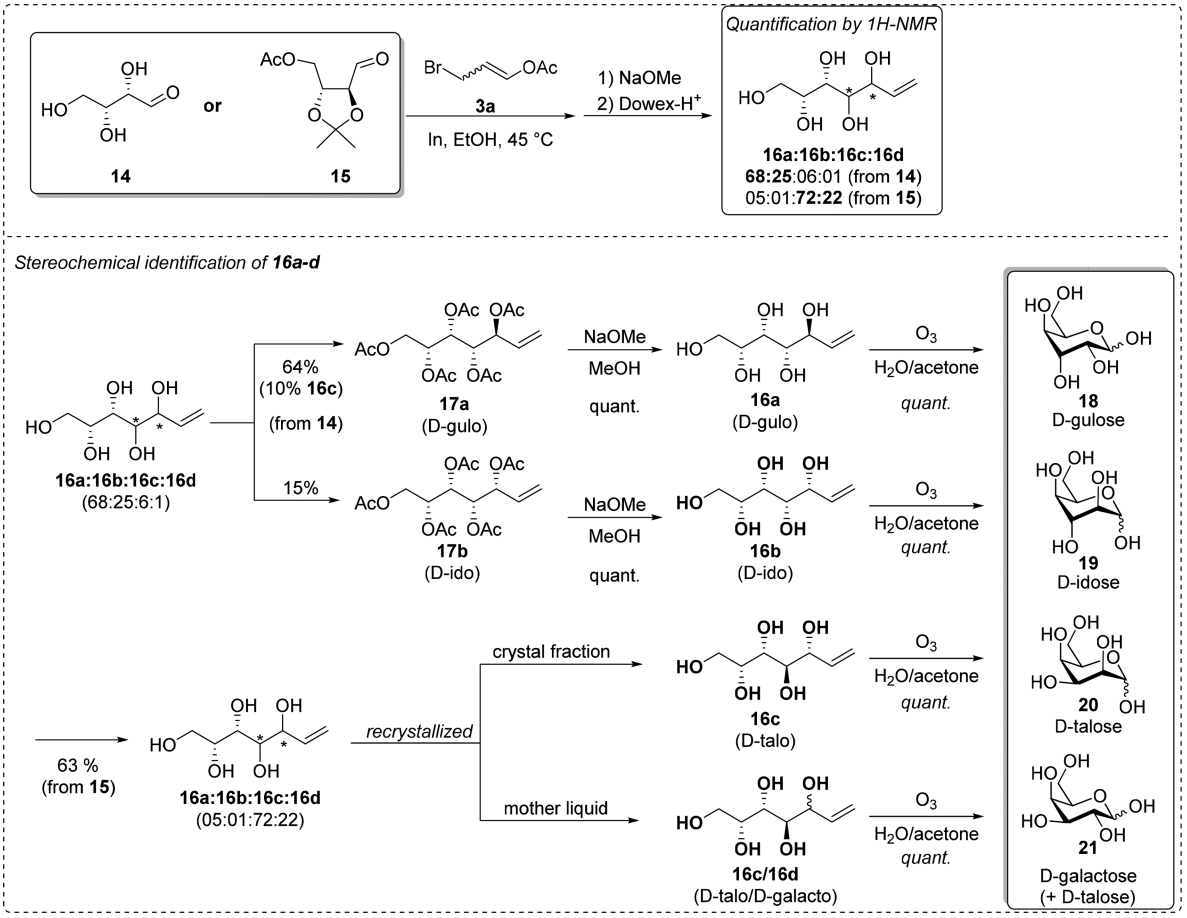
Acetyloxyallylation of protected and unprotected D-threose. Next, D-threose **14** (the 3-epimer of L-erythrose) and the related protected sugar aldehyde **15** were subjected to the same reaction conditions as indicated above (**3a**, In, EtOH, 45 °C). Compound **15** was prepared via a literature approach[24] with necessary modification of the final oxidation step.[25] Clean and full conversion was again achieved for both starting materials, and the crude reactions mixtures were processed to their fully unprotected enitols **16a−d** for quantification as described above (Scheme 3, top).

A very pronounced facial diastereodivergence between the conversion of unprotected (**14**) and protected D-threose **15** with a high degree of facial diastereoselectivity (>90%) was observed. In addition the simple diastereoselectivities were consistent with the *erythro*-case, in terms of both the types of addition products as well as their ratios (**14**: lyxo > xylo > ribo; **15**: ribo > arabino).[26] A comparably lower selectivity was observed in the conversion of **15** (~7:2 *anti:syn in the threo-case* versus ~7:1 in the *erythro*-case); it is noteworthy that due to different synthetic routes, *O4*-acetate protection was in place in **15** in contrast to the *O4*-formate in **7**. Purified diasteromers **16a−d** were obtained via chromatographic separation of the corresponding peracetates **17a−d** or by direct crystallization as in the separation of the *talo*- and *galacto*-configured enitols **17c/17d.** The stereochemical constitution was again proven by conversion to the reducing sugars (**18−21**) and comparison (^{1}H and ^{13}C NMR) to authentic commercial samples.

To facilitate the comparison of the results of the *erythro*- and *threo*-series, the corresponding product distributions are summarized in Figure 4, with reference to the stereochemical-type of addition rather than the actually formed structures.

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

Scheme 3. Facial Diastereodivergence in the Indium Mediated Addition of 3a to Unprotected (14) and Protected D-Threose (15)



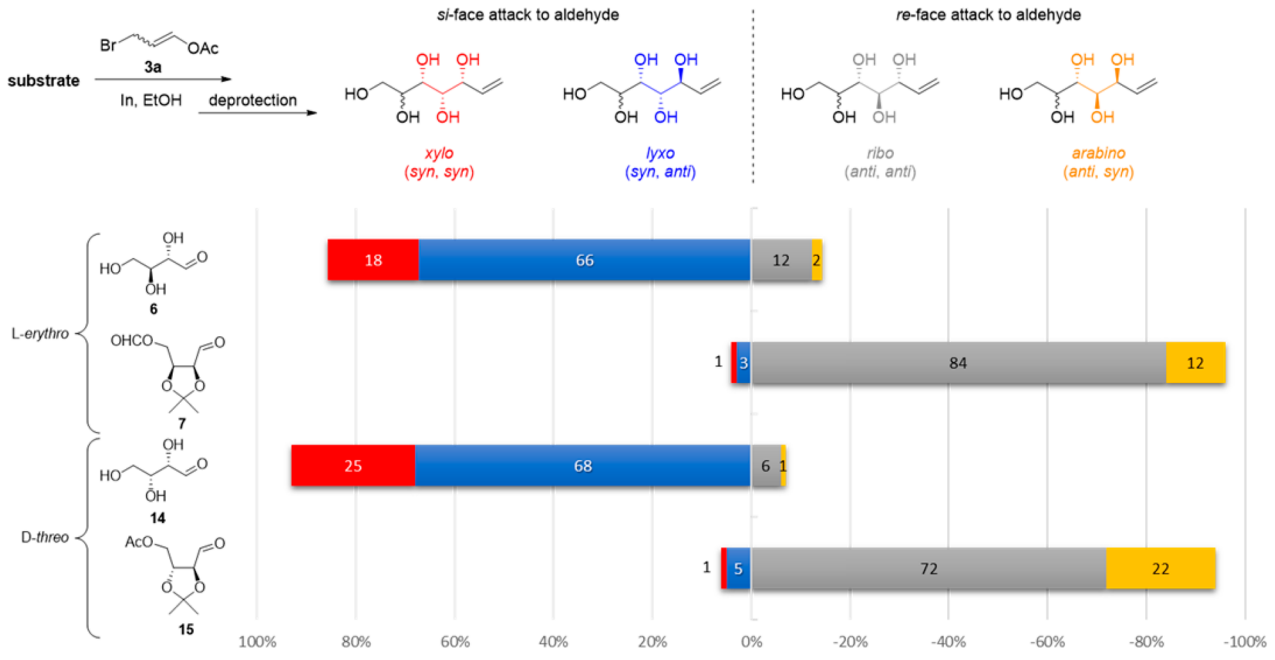


Figure 4. Summary of product-distributions in the acyloxylallylations of protected and unprotected tetroses (**6**, **7**, **14**, **15**). The formed products are referred to by the newly established relative stereochemistry (xylo, lyxo, ribo, arabino) to allow for comparison between the two series.

Optimization of the reagent to improve simple diastereoselectivity. Prompted by the moderate selectivities in the conversion of the unprotected tetroses (**6**, **14**), we decided to systematically investigate if the steric bulk of the ester moiety in the reagent can positively modulate the simple diastereoselectivity observed. Our hypothesis was based on the mechanistic

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

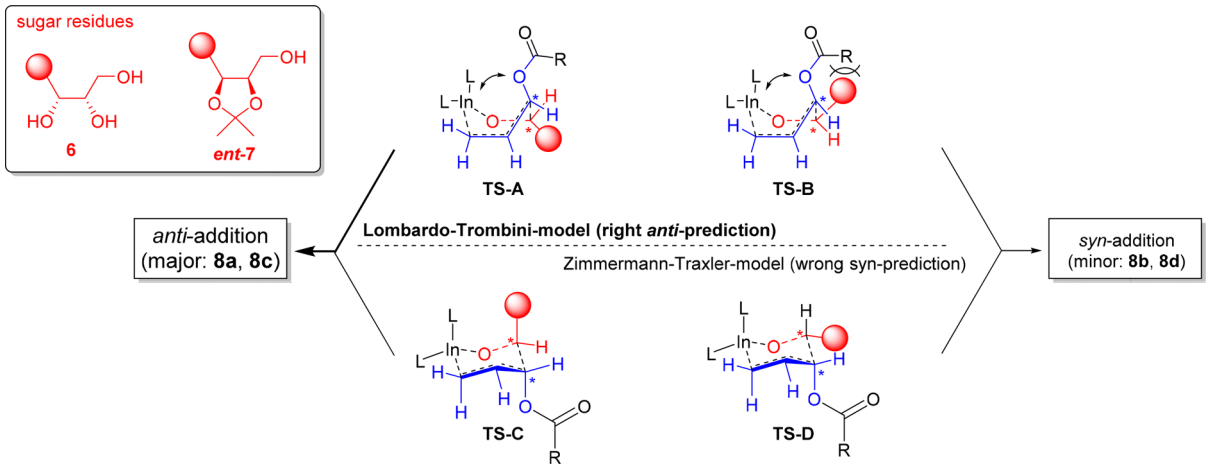


Figure 5. Mechanistic rational for the expected increase of simple diastereoselectivity with increasing bulk of the ester group due to steric clash with the sugar chain of **6** and **7** as examples. Instead of depicting the enantiomeric **ent-TS A** for the reaction with acetonide **7**, its enantiomer **ent-7** is depicted to account for the opposite facial selectivity correctly.

model established for simple achiral aldehydes by Lombardo and Trombini that aldoses apparently follow as well (Figure 5). The model rationalized the observed *anti*-selectivity with saturated aldehydes (and the stereocrossover with unsaturated aldehydes exhibiting *syn*-selectivity)[9,27] with a boat-like conformation in the relevant transition states (TS) which was further supported by an extensive computational study.[28] The boat-like conformation allows an additional positive stabilization of the metal center by the ester moiety (as in the y-*Z*-form of the parent indium organyl) which is not in place in the alternative classical Zimmerman−Traxler model. The TS leading to *syn* or *anti*-addition products according to the suggested model (top) and the alternative classical Zimmerman−Traxler model, predicting generally *syn*-addition, are depicted for the *erythro*-products **6** and **7** in Figure 5. Instead of showing an enantiomeric TS for **7**, enantiomeric **ent-7** is depicted to correctly represent the formation of the two different major *anti*-products.

According to the Lombardo−Trombini-model, the formation of an *anti*-isomer should be independent of the size of the ester moiety (**TS-A**) while the transition states leading to the *syn*-isomer (**TS-B** but even **TS-D**) would be affected by the steric congestion between the residue (sugar chain) and the ester group. Therefore, increasing bulk in the reactant would be expected to favor formation of the preferred *anti*-isomer (i.e., **8a**, **8c**).

To test this hypothesis, we synthesized a series of bromopropenyl esters with different steric demands (isobutyrate **3c**, pivalate **3d**, benzoate **3b**, 1-naphtoate **3e**, and mesitoate **3f**)[27] and utilized them in the acyloxyallylation of L-erythrose **6**. Iodopropenyl pivalate **22** (via the corresponding chloride **23**[28]) was included in the survey as a particularly reactive species to assist the replacement of indium by zinc as the mediating metal. It is noteworthy that, in all transformations of **3a−f** with indium, a full and clean conversion of **6** was achieved. Upon deacylation and subsequent GC-analysis, a stepwise increase of the simple diastereoselectivity (**8*a***/**8b**-ratio) was observed (**3a** < **3c** < **3d**, **3b**) (see Figure 6, lines 1−4). The application of the corresponding naphthoate **3e** did not give a significant additional increase in selectivity compared to benzoate **3b** (line 4−5) and an attempted investigation of mesitoate **3f**[29] (structure not shown) was hindered as, upon successful acyloxyallylation, the ester could not be cleaved to allow isomer-analysis. Of note the difference in selectivity between **3a** and **3d** is significantly more pronounced compared to our case study with L-lyxose, a pentose with the same stereochemistry at O2/O3 compared to **6**.[14]

Realization of the zinc-mediated acyloxyallylation of an unprotected sugar. The reaction of iodide **22** gave comparable product ratios to the standard bromide **3d** as mediated by indium; in addition it also showed complete product formation when reacted with zinc dust. This is in strong contrast to all earlier reports including our own experience with L-lyxose which failed to give any measurable conversion. To our best knowledge, this constitutes the first successful zinc-mediated acyloxyallylation of an unprotected aldose. However, closer analysis of the enitol product distribution revealed an entirely different picture compared to the use of indium. The observed product ratios (**8a**/**8b**/**8c**/**8d** = 38:9:40) indicated that the facial selectivity was completely lost while the *simple* diastereoselectivity remained in a similar range. The loss of facial selectivity under mediation of zinc was confirmed with other reagents (**3a** shown), revealing a striking difference in principle performance between indium and zinc in the acyloxyallylation of a chiral chelating starting material such as L-erythrose (Figure 6, lines 6−8). In contrast, the analogous experiment with acetonide **7**, **3a**, and zinc showed no detrimental effect on the facial-selectivity, providing comparable values to the alternative indium mediation (Figure 6, lines 9−10). For the latter case the study with chiral Garner's aldehyde can be considered a precedence.[9]

Mechanistic considerations for the zinc-mediated acyloxyallylation. Although the lost facial selectivity with zinc as mediator renders the replacement of indium synthetically irrelevant, it enables some interesting deductions to be elicited. The striking difference between the indium and zinc organyls supports an interpretation that the facial *syn*-selectivity observed in the unprotected case with indium (but not zinc) results from a chelating effect of the incoming organyl. The alternative explanation within the framework of a Cram-model would require the sugar chain of **5** to adopt an antiperiplanar orientation to the carbonyl (instead of the *O2* with **7**, Figure 3), but this would not explain the complete loss of facial selectivity when zinc is used. Nonetheless, the sole reactivity of L-erythrose **6** under zinc-mediated reaction is quite remarkable, and we hypothesize this originates from the exceptionally high proportion of the open chain form in tetroses (~10%) which would single them out from the all other longer-chain parent aldoses. The high concentration of available aldehyde species (and more

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

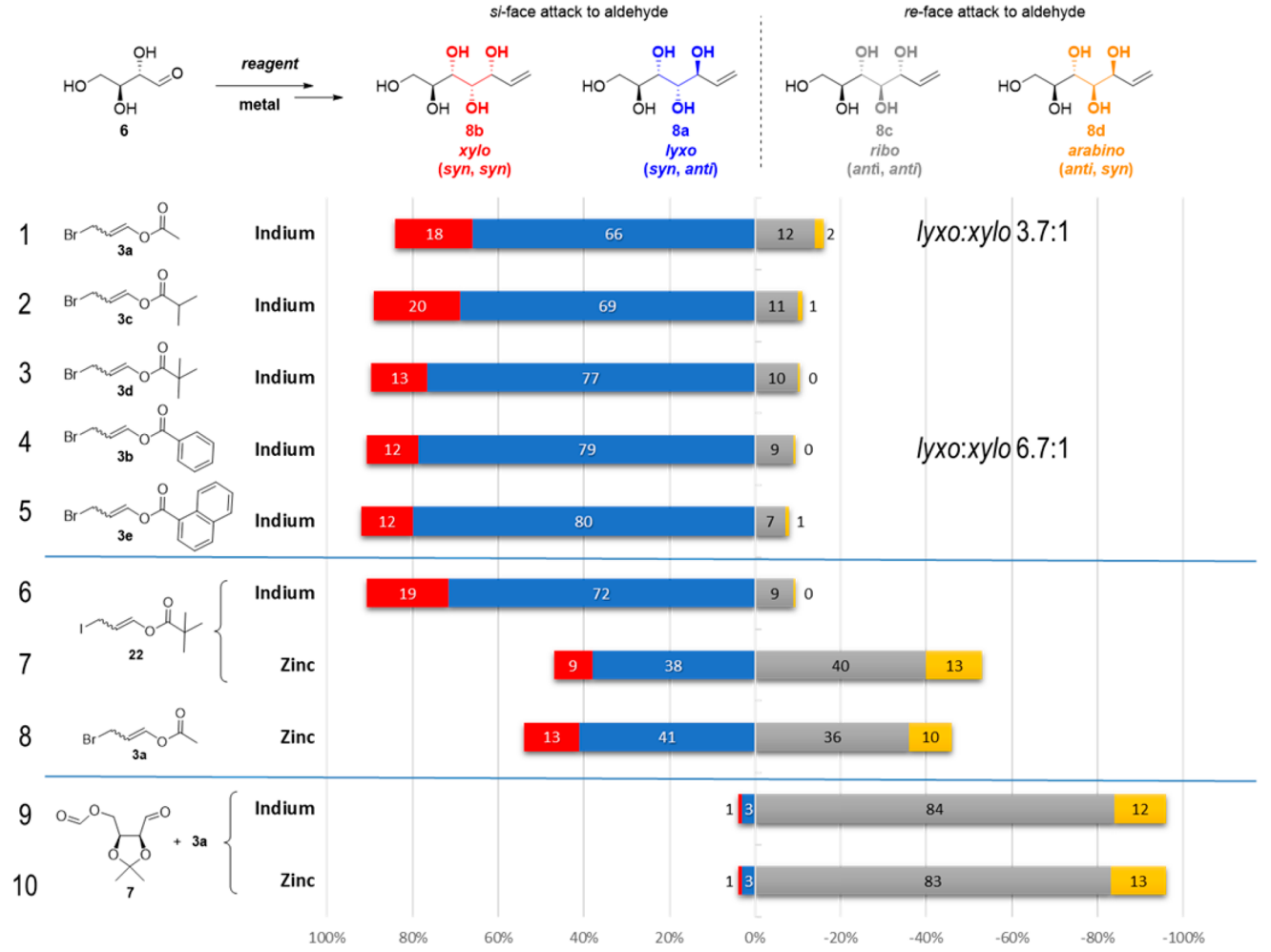


Figure 6. Product ratios of the acyloxyallylation of L-erythroses **6** and **7** depending on the used reagent and metal.

importantly, the fast re-equilibration to form this species) allows the acyloxyallylation under the mediation of zinc to take place rapidly. With the usual pentoses/hexoses, the (re)formation of the open chain structure from the dominant cyclic hemiacetal is apparently too slow to compete with reagent side reactions (e.g., Wurtz-type dimerization, alcoholysis).

Elucidation of the fate of halopropenylesters in alcoholic solutions. Only a short reaction time is required for complete and clean conversion in all indium-mediated acyloxyallylations with unprotected sugars, but an excess of reagent/indium is required and, importantly, sufficient stirring.[30] The fast formation of Wurtz-type byproducts in water has been reported[9] as a potential sink of reagent **3a**, which could not be confirmed by us in EtOH in blank experiments; only small amounts of material (potential Wurtz-type products) were recovered, with volatiles being the major side-products. In order to increase the understanding of the fate of the bromopropenyl esters under the protic conditions required to solubilize unprotected sugars, we dissolved **3a** in MeOH-d_4 and observed its rapid alcoholysis (to **25-d_6**) and slower conversion to the **26-d_{10}** (deuterated version of 1,1,3-trimethoxy propane **26**) over time (^{1}H NMR). The formation of **26-d_{10}** was supported by analogous reactions in MeOH and EtOH at preparative scale and comparison of isolates to commercial **26** and **27** (Scheme 4 and Supporting Information).

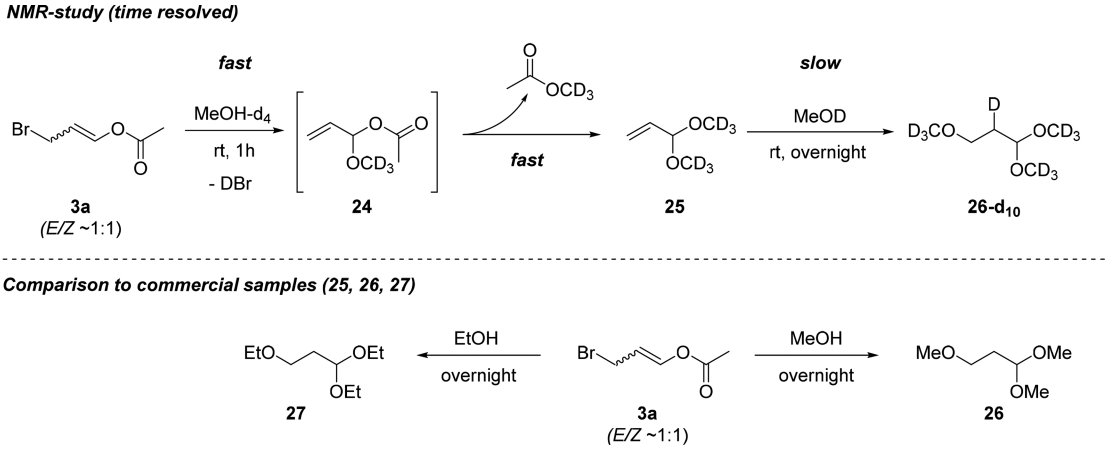
From this investigation we conclude that rapid alcoholysis consumes the reagent in competition with the formation of the indium organyl and in doing so liberates HBr which is responsible for the observed drop in pH and likely also for the formation of ethyl glycosides, observed in the case of incomplete initial conversion.[13,14] Under ideal reaction conditions, the formation of the indium organyl is fast enough to give a clean conversion even with standard reducing sugars (low content of open chain form). As indicated by the full conversion of **6**, the analogous zinc organyls can apparently be formed under the same reaction conditions, but more readily available aldehyde species are required to achieve acyloxyallylation (in time). This prerequisite is fulfilled in the case of L-erythrose but not with the other tested aldoses. Whether, under the indium mediation, the chelation with *O2* is not only responsible for the high degree of facial selectivity but also activates the reducing sugar toward the reaction cannot currently be answered.

CONCLUSION

With a coherent set of molecular probes (tetroses) we have undertaken an in-depth investigation of the indium and zinc-mediated acyloxyallylation of protected and unprotected tetrose structures. It has been shown that, independent of the relative stereochemistry at C2/C3, consistent product distributions (also to the one described by us earlier for L-lyxose) can be attained. A generally high facial selectivity is exhibited, outlining a strong substrate control with respect to the stereochemistry in the α-position to the reactive carbonyl. Furthermore, a pronounced

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

Scheme 4. Fate of Bromopropenylacetate 3a in Alcoholic Solutions (at NMR and preparative scale)



diastereodivergence was observed depending on whether or not *O2/O3*-isopropylidene protection was in place. Increasing bulk in the ester group promotes the selectivity for the *lyxo*-type addition to L-erythrose, an observation which is consistent with the model established for achiral aldehydes. With unprotected L-erythrose, we accomplished for the first time the replacement of indium by zinc as the acyloxyallylation mediator; however, the high facial selectivity observed with indium was entirely lost, a striking difference between the two metals which can only be observed in this complex setting of a chelating chiral starting material. This observation is a beautiful example of the value of including other more exotic sugars into methodological work. Through a structured and detailed investigation of the indium and zinc-mediated acyloxyallylation of tetroses, several outstanding questions pertaining to this attractive but complex transformation have finally been clarified. This consolidated knowledge allows for more refined predictions, and we hope it will inspire more people to consider acyloxyallylation as a synthetic tool, within and beyond the realm of carbohydrate chemistry. Applications toward further short synthetic routes to currently rare and exotic sugars based on acyloxyallylation are currently being developed in our lab.

EXPERIMENTAL SECTION

General Methods. All starting materials and reagents as well as the reference materials for D-hexoses (Carbosynth, UK) were purchased from commercial sources and used without further purification. Dowex 50WX2 hydrogen form was used as an acidic ion-exchange resin. Reactions were monitored by TLC on silica gel 60 F254 plates; spots were detected by UV light examination or visualized by spraying with anisaldehyde−sulfuric acid and heating. Normal-phase column chromatography was performed on silica gel 60 (230−400 mesh). NMR spectra were recorded at 297 K in the solvent indicated, with 400 and 600 MHz instruments, respectively, employing standard software provided by the manufacturer. ^{1}H NMR and ^{13}C NMR spectra were referenced to tetramethylsilane (TMS, δ = 0) by calibration with the residual organic solvent signals.[31] All assignments are based on COSY, HSQC, and HMBC experiments. Accurate mass analysis (2 ppm mass accuracy) was carried out from 10−100 mg/L solutions via LC−TOFMS measurements using an autosampler, an HPLC system with binary pumps, degasser, and column thermostat and ESI-TOF mass spectrometer. Optical rotation was determined from solution of the indicated solvent and measured on an Anton Paar MCP 300 circlepolarimeter. The used cuvette was a 100 mm-cell with serial number: 16037274. Melting points were determined with a Büchi Melting Point B-545 apparatus with a heating rate of 1 °C min^{-1} (70% onset point and 10% clear point) or on a Kofler Block apparatus. Compounds **3a**,[27] **3b**,[27] **4**−**5**,[20] and **23**[32] were prepared according to known literature procedures. Compounds 3c-e, 7 and 22 reproducibly did not give conclusive HRMS results which was attributed to their labile nature which also prevented purification to the high purity required for elemental analysis.

Determination of enitol distribution derived from *erythro*-configured starting materials (GC). *Synthesis of heptenitoles 8a-d starting from L-erythrose 6 on analytical scale.* L-Erythrose **6** (0.1−0.4 mmol) was dissolved in dry EtOH (0.2 M) and heated to 45 °C. Then, the corresponding halopropenyl ester (3.00 equiv) and indium or zinc (2.00 equiv) were added under vigorous stirring and in immediate succession. After 30 min complete conversion of starting material (staining yellow/green) to a more apolar spot (staining blue) was obtained according to TLC analysis (DCM/MeOH 9:1). The reaction mixture was filtered and solvent and volatiles evaporated.[33] The white residue was taken up in MeOH (0.1 M) and NaOMe was added until a basic pH was reached, which led to the formation of a white precipitate. The reaction mixture was stirred at rt until TLC analysis (DCM/MeOH 9:1) showed complete conversion to a more polar spot when the white precipitate was centrifuged and the supernatant was neutralized with Dowex-H^{+}. The resin was filtered and an aliquot of the filtrate was subjected to GC analysis.

Synthesis of heptenitoles 8a-d starting from 2/3O-protected erythrose 7. Dry EtOH (0.1 M) was heated to 45 °C in a round-bottom flask. In immediate succession, first indium or zinc (2.00 equiv), freshly distilled 3-bromoprop-1-en-1-yl acetate **3a** (3.00 equiv) and subsequently aldehyde **7** (1.00 equiv, 0.1−0.4 mmol) was added as a solution in little EtOH in one portion. The reaction mixture was stirred at 45 °C for 30 min, when TLC (LP/EtOAc 1:1) showed complete conversion to a more apolar product (staining blue; starting material yellow). The reaction mixture was filtered and the filtrate was evaporated, leaving a white residue, which was acetylated using Ac_2O in pyridine, followed by aqueous workup to remove all inorganics. The acetylated product mixture was taken up in dry MeOH and treated with NaOMe until a pH of 9−10 was reached. The mixture was stirred at rt for 1 h, when reaction monitoring via TLC (LP/EtOAc 1:1 and 1:3) showed complete conversion to a more polar spot. The reaction mixture was neutralized by addition of Dowex-H^{+} resin and filtered. Fresh (MeOH washed) Dowex-H^{+} was added until a pH < ∼2 was determined and the reaction mixture was stirred at rt for 2 h, when reaction monitoring via TLC (DCM/MeOH 9:1) showed complete conversion to fully unprotected heptenitoles **8a**−**d**. The resin was filtered and an aliquot was subjected to GC analysis.

Persilylation (OTMS) of crude enitols 8a-d and GC-analysis. An aliquot (containing approximately 0.1−0.2 mg of enitole species) of crude enitol containing solutions was evaporated to dryness. To the dry residue, glycerol (silylation standard) was added in ∼ equimolar amounts. The mixture was taken up in a solution of DMAP in pyridine (c(DMAP) 0.75 mg/mL; 400 μL). *N,O*-Bis(trimethylsilyl)trifluoroacetamide (200 μL, incl. 1% (v/v) TMSCl) was added and the mixture was

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

stirred at 70 °C for 4 h. EtOAc (400 μL) was added and after filtration through a syringe filter, the samples were analyzed via GC. The ratio of diastereomers was determined by gas chromatography (GC) using a Thermo Finnigan Focus GC/DSQ II equipped with a standard capillary column (BGB5, 30 m x 0.25 mm ID, 0.50 μm film) and a FID detector. carrier gas: helium, injector: 230 °C; column flow: 2.0 mL/min; oven program: 50−190 °C (50 °C/min) → 190−220 °C (3 °C/min) → 220−310 °C (50 °C/min) → 310 °C (2 min). Retention times: 9.62 (**8c**), 9.75 (**8a**), 9.85 (**8b**), 9.98 (**8d**) min.

Determination of enitol distribution derived from *threo*-configured starting materials (^{1}H NMR). *Synthesis of heptenitoles 17a-d (peracetates) starting from* D*-threose 14 on analytical scale.* D-Threose **14** (0.5 mmol) was dissolved in dry EtOH (0.2 M) and heated to 45 °C and bromopropenyl acetate **3a** (3.00 equiv) and indium (2.00 equiv) were added under vigorous stirring in immediate succession. After 30 min complete conversion of starting material (staining yellow/green) to a more apolar spot (staining blue) was obtained according to TLC analysis (DCM/MeOH 9:1). The reaction mixture was filtered and solvent and volatiles evaporated. The white residue was acetylated with Ac_2O in pyridine followed by an acidic aqueous workup to remove all inorganics. The crude mixture was analyzed by ^{1}H NMR to determine the enitol ratios by comparison to reference materials (*see* Supporting Information *for a comparison of the crude mixture with purified* ***17a-c***).

Synthesis of heptenitoles 16a-d starting from 2/3O-protected D*-threose 15.* Dry EtOH (0.1 M) was heated to 45 °C in a round-bottom flask. In immediate succession, first indium (2.00 equiv), freshly distilled 3-bromoprop-1-en-1-yl acetate **3a** (3.00 equiv) and subsequently aldehyde **15** (1.00 equiv, 0.1−0.4 mmol) was added as a solution in little EtOH in one portion. The reaction mixture was stirred at 45 °C for 30 min, when TLC (LP/EtOAc 1:1) showed complete conversion to a more apolar product (staining blue; starting material yellow). The reaction mixture was filtered and the filtrate was evaporated, leaving a white residue, which was acetylated with Ac_2O in pyridine, followed by aqueous workup to remove all inorganics. The acetylated product mixture (**17a−d**) was taken up in dry MeOH and treated with NaOMe until a pH of 9−10 was reached. The mixture was stirred at rt for 1 h, when reaction monitoring via TLC (LP/EtOAc 1:1 and 1:3) showed complete conversion to a more polar spot. The reaction mixture was neutralized by addition of Dowex-H^+ resin and filtered. Fresh (MeOH washed) Dowex-H^+ was added until a pH < ∼2 was determined and the reaction mixture was stirred at rt for 2 h, when TLC-analysis (DCM/MeOH 9:1) indicated complete conversion to the fully unprotected heptenitoles **16a−d**. The resin was filtered, the filtrate was evaporated and passed over a short bed of SiO_2 (DCM/MeOH 4:1) to separate reagent based side-products and the crude enitol mixture was analyzed by ^{1}H NMR (*see* Supporting Information).

General procedure 1 for the ozonolysis of enitoles. Heptenitol (1.00 equiv) was dissolved in 3:2 H_2O/acetone (2% (w/v)). A small amount of Sudan red III in acetone (as indicator) was added and the mixture was cooled with an ice-bath. Ozone was bubbled through the reaction through a gas inlet tube, the gas outlet was passed through an aq. KI (10% w/w) solution in a gas wash bottle. As soon as the bright pink color of the indicator diminished, TLC analysis ($CHCl_3$/MeOH/H_2O 14:6:1) was carried out to confirm complete conversion of starting material to a more polar, smearing spot. Oxygen was bubbled through the solution for ∼15 min before additional acetone (to solubilize the PPh_3) and PPh_3 (2.00 equiv) were added and stirring was continued at rt overnight when peroxide tests (test stripes) indicated complete reduction of all peroxides and H_2O_2. The reaction mixture was concentrated and the remaining aqueous layer was washed with DCM, EtOAc and Et_2O before it was lyophilized and coevaporated from MeOH twice (removing HCHO) to obtain the corresponding hexose.

*3-Bromoprop-1-en-1-yl isobutyrate (**3c**).* Acrolein (95%, 7.14 mL, 107 mmol, 1.00 equiv) was dissolved in dry DCM (85 mL) and cooled to −20 °C, using an acetone/liquid N_2 cooling bath. First, isobutyryl bromide (9.03 g, 101 mmol, 0.95 equiv) followed by anhydrous $ZnCl_2$ (0.15 g, 1.07 mmol, 0.01 equiv) was added. The reaction mixture was stirred and allowed to warm by lowering the cooling bath until −15 °C, when an exothermic reaction caused warming up to +10 °C. The flask was reimmersed in the cooling bath and the temperature was kept under −10 °C for 1 h. A sample (micro workup with Et_2O and aq. $NaHCO_3$ and drying with $MgSO_4$) for analysis via ^{1}H NMR was taken, confirming complete conversion of starting material to the target products. Under cooling H_2O (40 mL) was added (temperature rose to −10 °C), which led to the formation of a white precipitate. Layers were separated and the organic layer washed with H_2O (still acidic) and sat. aq. $NaHCO_3$ (until basic pH). The organic layer was washed with brine, dried over $MgSO_4$ and the solvent evaporated, leaving a brown liquid (17.3 g) which was purified by distillation (bp 43 °C, 0.4 mbar) to give pure target compound **3c** as colorless liquid (9.00 g, 41%): ratio of *E*/*Z* = 1:1.4; (*E*)-isomer ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (dt, *J* = 12.4, 1.1 Hz, 1H, =C***H***−O), 5.71 (dt, *J* = 12.4, 8.4 Hz, 1H, CH_2−C***H***=), 4.00 (dd, *J* = 8.5, 1.0 Hz, 2H, CH_2−Br), 2.63 (hept, *J* = 7.0 Hz, 1H, C***H***-$(CH_3)_2$), 1.21 (d, *J* = 7.0 Hz, 6H, CH−(C***H***$_3)_2$); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.7 (s, C=O), 139.5 (d, O−CH=), 111.1 (d, =***C***H−CH_2), 33.8 (d, ***C***H−$(CH_3)_2$), 28.8 (t, −CH_2−Br), 18.7 (q, −CH_3) ; (*Z*)-isomer: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (dt, *J* = 6.3, 0.8 Hz, 2H, =C***H***−O), 5.25 (td, *J* = 8.4, 6.3 Hz, 1H, CH_2−C***H***=), 4.08 (dd, *J* = 8.4, 0.8 Hz, 2H, CH_2−Br), 2.70 (hept, *J* = 7.0 Hz, 1H, C***H***-$(CH_3)_2$), 1.25 (d, *J* = 7.0 Hz, 6H, CH−(C***H***$_3)_2$); ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.3 (s, C=O), 137.5 (d, O−CH=), 109.5 (d, =***C***H−CH_2), 34.0 (d, ***C***H−$(CH_3)_2$), 23.7 (t, −CH_2−Br), 18.8 (q, −CH_3);

*3-Bromoprop-1-en-1-yl pivalate (**3d**).* Step 1 - synthesis of pivaloyl bromide: PPh_3 (26.2 g, 0.1 mol, 1.00 equiv) was dissolved in dry DCM (50 mL) and cooled to 0 °C via an ice-bath. Br_2 (5.12 mL, 0.1 mol, 1.00 equiv) was added as a solution in dry DCM (50 mL) dropwise, keeping the temperature at 0 °C. PPh_3Br_2 started to precipitate. After complete addition of Br_2, pivalic acid was also dissolved in dry DCM (50 mL) and added quickly to the reaction mixture. The previously formed precipitate got dissolved and stirring was continued at rt for 1 h. Solvent was evaporated and the residue was treated with dry Et_2O, which led to the formation of a lot of precipitate, which was filtered and the solvent was evaporated. The product **3d** was obtained by distillation under reduced pressure as a colorless liquid (5.3 g, 32%): bp 25 °C, 10 mbar (lit.[34] 65 °C, 15 Torr); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.30 (s, 1H, 3 × CH_3); ^{13}C NMR (101 MHz, $CDCl_3$) δ = 178.8 (COBr), 52.8 (*C*$(CH_3)_3$), 27.2 (3 × CH_3). *Step 2:* Acrolein (95%, 2.38 mL, 35.7 mmol, 1.00 equiv) was dissolved in dry DCM (14 mL) and cooled to −20 °C, using an acetone cooling bath. Then, pivaloyl bromide (5.30 g, 32.1 mmol, 0.95 equiv) was added and subsequently anhydrous $ZnCl_2$ (40 mg, 0.32 mmol, 0.01 equiv). The reaction mixture was stirred and allowed to warm to −15 °C, when an exothermic reaction caused warming up to +10 °C. The flask was immersed in the cooling bath again and the temperature was kept under −10 °C for an hour and a sample (micro workup with Et_2O and aq. $NaHCO_3$ and drying with $MgSO_4$) for analysis via ^{1}H NMR was taken. This showed complete conversion of starting material to the desired product. H_2O (10 mL) was added under cooling (temperature rise to −10 °C. Layers were separated and the organic layer washed with H_2O (still acidic) and sat. aq. $NaHCO_3$ (until basic pH). Then, the organic layer was washed with brine, dried over $MgSO_4$ and the solvent evaporated, leaving a brown liquid (9.03 g). The product **3d** was obtained by distillation under reduced pressure as a colorless liquid (3.00 g, 42%): bp 38 °C, 0.2 mbar; ratio of *E*/*Z* 1:1.7; (*E*)-isomer ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 (dt, *J* = 12.4, 1.0 Hz, 1H, =CH−O), 5.70 (dt, *J* = 12.4, 8.5 Hz, 1H, =C***H***−CH_2), 3.99 (dd, *J* = 8.5, 1.1 Hz, 2H, CH_2−Br), 1.23 (s, 9H, 3× CH_3); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.2 (C=O), 139.7 (d, O−CH=), 111.1 (d, =***C***H−CH_2), 28.9 (t, CH_2−Br), 27.0 (q, 3× C(***C***$H_3)_3$); (*Z*)-Isomer ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 (dt, *J* = 6.2, 0.8 Hz, 1H, =CH−O), 5.25 (td, *J* = 8.3, 6.2 Hz, 1H, =C***H***−CH_2), 4.07 (dd, *J* = 8.4, 0.8 Hz, 2H, CH_2−Br), 1.28 (s, 9H, 3× CH_3), ^{13}C NMR (101 MHz, $CDCl_3$) δ 174.7 (C=O), 137.9 (d, O−CH=), 109.6 (d, =***C***H−CH_2), 39.2 (***C***$(CH_3)_3$), 38.9 (***C***$(CH_3)_3$); 27.1 (q, 3 × C(***C***$H_3)_3$), 23.6 (t, CH_2−Br);

*3-Bromoprop-1-en-1-yl naphthoate (**3e**).* A solution of PPh_3 (3.05 g, 11.6 mmol, 1.00 equiv) in dry DCM (6 mL) was cooled to 0 °C via an ice-bath before Br_2 (0.60 mL, 11.6 mmol, 1.00 equiv) was added dropwise as a solution in dry DCM (6 mL), keeping the temperature at 0 °C. PPh_3Br_2 started to precipitate. After complete addition of Br_2,

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

naphthoic acid was added to the reaction mixture. The previously formed precipitate got dissolved and stirring was continued at rt for 1 h. The solvent was evaporated and the residue was treated with Et_2O/hexane (1:1, 25 mL), which led to the formation of a lot of precipitate, which was filtered and the solvent was evaporated. The product was obtained by distillation under reduced pressure as a colorless liquid (2.00 g, 73%): bp 175 °C, 1.7 mbar (lit.[35] 129−132 °C, 2 Torr) and used without further purification. Acrolein (95%, 0.57 mL, 8.51 mmol, 1.00 equiv) was dissolved in dry DCM (20 mL) and cooled to −20 °C, using an acetone cooling bath. Then, naphthoic acid bromide (2.00 g, 8.51 mmol, 0.95 equiv) was added and subsequently anhydrous $ZnCl_2$ (12 mg, 0.09 mmol, 0.01 equiv). The reaction mixture was stirred and allowed to warm to rt and kept stirring at this temperature for 30 min. The whole mixture was poured onto H_2O/ice and the product was extracted with Et_2O (200 mL). Phases were separated and the organic layer washed with sat.aq. $NaHCO_3$ and brine. Then it was dried over $MgSO_4$ and the solvent evaporated, leaving a brown liquid, which solidified upon storage at −18 °C (2.05 g, 81%). The product **3e** was used without further purification. ratio of E/Z = 1:1.3; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.97 (t, J = 7.8 Hz, 1.1H, Ar), 8.33 (dd, J = 16.9, 7.3 Hz, 1H, Ar), 8.09 (t, J = 8.0 Hz, 1.2H, Ar), 7.91 (dd, J = 8.1, 4.9 Hz, 1.3H, Ar), 7.78 (d, J = 12.4 Hz, 0.4H, =CH−O (E)), 7.72−7.61 (m, 1.2H, Ar, =CH−O (Z)), 7.62−7.48 (m, 3H, Ar), 5.93 (dt, J = 12.4, 8.4 Hz, 0.4H, =CH− (E)), 5.43 (td, J = 8.4, 6.3 Hz, 0.6H, =CH− (Z)), 4.23 (d, J = 8.4 Hz, 1.2H, CH_2−Br (Z)), 4.11 (d, J = 8.4 Hz, 0.9H, CH_2−Br (E)); ^{13}C NMR (101 MHz, $CDCl_3$) δ 163.7 (C=O(E)), 163.3 (C=O(Z)), 139.6 (=CH−O (E)), 137.8 (=CH−O (Z)), 134.84 (ArCH), 134.78 (ArCH), 134.0 (ArC), 133.98 (ArC), 131.74 (ArC), 131.72 (ArC), 131.42 (ArCH), 131.40 (ArCH), 128.88 (ArCH), 128.86 (ArCH), 128.5 (ArCH), 128.4 (ArCH), 126.7 (ArCH), 126.6 (ArCH), 125.72 (ArCH), 125.67 (ArCH), 125.0 (ArC), 124.8 (ArC), 124.65 (ArCH), 124.56 (ArCH), 111.9 (=CH− (E)), 110.1 (=CH− (Z)), 28.9 (CH_2−Br (E)), 24.0 (CH_2−Br (Z)).

*L-Erythrose (**6**).* Acetonide **5**[20] (2.70 g, 16.9 mmol, 1.00 equiv) was taken up in H_2O (27 mL) and Dowex-H$^+$ (freshly washed with H_2O) was added and the mixture was heated to 80 °C for around 30 min. The mixture was allowed to cool to rt, was filtered over Celite, washed with fresh water (3 ×) and was lyophilized to give pure L-erythrose (2.02 g, quant.) according to NMR, observed in a mixture of two furanose forms and around ∼10% of the open chain form as hydrate which is consistent with the literature.[36]

*4-O-Formyl-2,3-O-isopropylidene-L-erythrose (**7**).* Solid SiO_2−$NaIO_4$ (14% (w/w), 52 g, 2.00 equiv) was added to a solution of 3,4-*O*-isopropylidine L-arabinose[20] **2** (3.20 g, 16.8 mmol, 1.00 equiv) in DCM (65 mL) in one portion at rt. The flask was closed and shaken vigorously. After stirring 30 min at room temperature, reaction monitoring via TLC (LP/EtOAc 1:1) showed complete conversion of starting material to a more apolar and smearing spot (staining differently). The reaction mixture was filtered and the silica gel was washed with fresh DCM (250 mL). After evaporation of the solvent, the product **7** was obtained as a colorless oil in good purity and used without further purification (2.50 g, 79%): R_f 0.58 (LP/EtOAc 1:1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.69 (d, J = 2.2 Hz, 1H, H1), 8.01 (q, J = 0.8 Hz, 1H, OCHO), 4.58 (ddd, J = 8.3, 5.1, 3.5 Hz, 1H, H3), 4.44 (m, 2H, H4a and H2), 4.07 (ddd, J = 12.2, 5.1, 0.8 Hz, 1H, H4b), 1.55 (s, 3H, CH_3), 1.38 (s, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$) δ 201.2 (C1), 160.1 (OCHO), 111.4 ($\mathbf{C}(CH_3)_2$), 80.4 (C2), 75.9 (C, 60.9 (C4), 26.9 (CH_3), 24.9 (CH_3).

*1,2-Dideoxy-L-manno-hept-1-enitol (**8a**).* The L-*manno* enitol peracetate **9a** (540 mg, 1.39 mmol, 1.00 equiv) was dissolved in dry MeOH (20 mL) and NaOMe (8 mg, 0.14 mmol, 0.10 equiv) was added. After 1 h TLC analysis (LP/EtOAc 3:1, DCM/MeOH 4:1) indicated all material was converted to the target compound. The reaction mixture was neutralized by addition of freshly washed ion-exchange resin, filtered, washed with fresh MeOH and evaporated to leave pure target compound (195 mg, 79%) as a colorless oil, which solidified during storage. m.p.: 97.9−99.0 °C (Et_2O); R_f 0.31 (DCM/MeOH 4:1); $[\alpha]_D^{20}$ −22 (c 1.0, MeOH); ^{1}H NMR (400 MHz, MeOD) δ 6.05 (ddd, J = 17.2, 10.6, 5.7 Hz, 1H, H2), 5.34 (dt, J = 17.3, 1.7 Hz, 1H, H1a), 5.19 (dt, J = 10.6, 1.6 Hz, 1H, H1b), 4.21−4.13 (m, 1H, H3), 3.84−3.76 (m, 2H, H5, H7a), 3.73−3.58 (m, 3H, H4, H6, H7b); ^{13}C NMR (101 MHz, MeOD) δ 140.4 (C2), 115.9 (C1), 74.3 (C3), 73.4 (C4), 73.0 (C6), 71.5 (C5), 65.1 (C7); HRMS ($^+$ESI-TOF) m/z [M + H] calcd for $C_7H_{15}O_5$ 179.0914, found 179.0921; HRMS (-ESI-TOF) m/z [M − H]$^-$ calcd for $C_7H_{13}O_5$ 177.0768, found 177.0772;

*1,2-Dideoxy-L-gluco-hept-1-enitol (**8b**).* The L-*gluco* peracetate **9b** (50 mg, 0.129 mmol, 1.00 equiv) was dissolved in dry MeOH (2 mL) and NaOMe (1 mg, 0.013 mmol, 0.1 equiv) was added, pH was checked to be basic. After 1 h TLC analysis (LP/EtOAc 3:1 and DCM/MeOH 4:1) indicated all material was converted to the target compound. The reaction mixture was neutralized by addition of freshly washed (MeOH) acidic ion-exchange resin, filtered washed with fresh MeOH and evaporated to leave pure target compound (21 mg, 92%) which solidified on drying from Et_2O solution. m.p.: 104.0−105.9 °C (Et_2O); R_f 0.31 (DCM/MeOH 4:1); $[\alpha]_D^{20}$ + 9.4 (c 1.0, MeOH); ^{1}H NMR (400 MHz, MeOD) δ 5.91 (ddd, J = 17.3, 10.5, 6.8 Hz, 1H, H2), 5.35 (ddd, J = 17.3, 1.8, 1.3 Hz, 1H, H1a), 5.19 (ddd, J = 10.5, 1.9, 1.0 Hz, 1H, H1b), 4.19 (t, J = 6.9 Hz, 1H, H3), 3.78 (dd, J = 11.1, 3.4 Hz, 1H, H7a), 3.75−3.65 (m, 2H, H4, H6), 3.60 (dd, J = 11.1, 5.8 Hz, 1H, H7b), 3.56 (dd, J = 8.3, 1.3 Hz, 2H, H5); ^{13}C NMR (101 MHz, MeOD) δ 139.2 (C2), 117.2 (C1), 75.8 (C3), 73.9, 72.9 (C4, C6), 72.6 (C5), 64.9 (C7). found 179.0921; HRMS ($^-$ESI-TOF) m/z [M − H]$^-$ calcd for $C_7H_{13}O_5$ 177.0768, found 177.0770;

*1,2-Dideoxy-L-allo-hept-1-enitol (**8c**) and 1,2-Dideoxy-L-altro-hept-1-enitol (**8d**).* Dry EtOH (150 mL) was heated to 45 °C in a round-bottom flask. In immediate succession, first indium (3.05 g, 26.6 mmol, 2.00 equiv), freshly distilled bromopropenyl acetate **3a** (8.49 g, 39.9 mmol, 3.00 equiv) and subsequently aldehyde **7** (2.50 g, 13.3 mmol, 1.00 equiv) was added as a solution in little EtOH in one portion. Heating was removed and the temperature rose to approximately 60 °C. After the temperature began to decrease again, the reaction mixture was stirred at 45 °C for 30 min, when TLC (LP/EtOAc 1:1) showed complete conversion to a more apolar product (staining blue; starting material yellow). The reaction mixture was filtered and the filtrate was evaporated, leaving a white residue, which was taken up in pyridine (80 mL) and treated with acetic anhydride (60 mL) forming a solution. Next, DMAP (20 mg, 0.16 mmol) was added and stirring was continued at rt overnight, when TLC analysis (LP/EtOAc 1:1) indicated complete conversion. The reaction mixture was immersed into an ice-bath and MeOH (80 mL) was added and the reaction mixture was stirred for ten min, before it was diluted with EtOAc and transferred to a separatory funnel. The organic layer was washed with ice-cold 1 N HCl, water, sat. aq. $NaHCO_3$, brine and dried over $MgSO_4$. The solvent was evaporated leaving a slightly yellow, highly viscous liquid (5.70 g). This residue was taken up in dry MeOH and treated with NaOMe until a pH of 9−10 was reached. The mixture was stirred at rt for 1 h, when reaction monitoring via TLC (LP/EtOAc 1:1 and 1:3) showed complete conversion to very polar spot. The reaction mixture was neutralized by addition of Dowex-H+ resin and filtered. Fresh (MeOH washed) Dowex-H$^+$ (9.4 g) was added and the reaction mixture was stirred at rt for 24 h, when reaction monitoring via TLC (DCM/MeOH 9:1) showed complete conversion to unprotected enitoles. Dowex-H$^+$ was filtered, the solvent was evaporated and the residue was taken up in H_2O, washed with DCM, EtOAc and Et_2O and the aqueous layer was evaporated (2.50 g). The crude material was purified vacuum column chromatography on silica gel (40 g, DCM/MeOH 9:1 → 4:1) to give targeted enitoles **8c** and **8d** in inseparable mixture as a highly viscous, colorless oil (1.75 g, 73%, *allo*:*altro* ∼ 9:1):

Analytical data for **8c** (L-*allo*): R_f: 0.71 ($CHCl_3$/MeOH/H_2O 14:6:1); ^{1}H NMR (400 MHz, MeOD) δ 6.01 (ddd, J = 17.2, 10.5, 6.6 Hz, 1H, H2), 5.32 (ddd, J = 17.3, 2.1, 1.3 Hz, 1H, H1a), 5.21 (ddd, J = 10.5, 2.0, 1.1 Hz, 1H, H1b), 4.28 (ddt, J = 6.1, 4.7, 1.2 Hz, 1H, H3), 3.91−3.73 (m, 2H, H5 and H7a), 3.73−3.57 (m, 3H, H4, H6 and H7b); ^{13}C NMR (101 MHz, MeOD) δ 138.5 (C2), 117.0 (C1), 76.5 (C6), 75.1 (C3), 74.3 (C5), 74.0 (C4), 64.1 (C7); HRMS ($^+$ESI-TOF) m/z [M + Na]$^+$ calcd for $C_7H_{14}NaO_5$ 201.0733, found 201.0752.

*1,2-Dideoxy-L-manno-hept-1-enitol hexaacetate (**9a**) and 1,2-Dideoxy-L-gluco-hept-1-enitol hexaacetate (**9b**).* Freshly prepared L-erythrose **6** (0.371 g, 3.09 mmol, 1.00 equiv) was dissolved in dry EtOH (30 mL) and was heated to 40 °C. First, indium (0.709 g, 6.18 mmol,

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

2.00 equiv) and then bromopropenyl acetate **3a** (1.69 g, 9.26 mmol, 3.00 equiv) was added and the mixture was stirred for 10 min. According to TLC (DCM/MeOH 4:1) all starting material was converted to a less polar material (staining blue). The reaction mixture was filtered, evaporated, taken up in pyridine (5 mL) and Ac_2O (3.7 mL, 37.0 mmol, 12.0 equiv) was added under ice-bath cooling. After 15 min, a small amount of DMAP was added and stirring was continued at rt overnight. Upon complete conversion (TLC, DCM/MeOH 4:1, LP/EtOAc 1:1), the excess of Ac_2O was quenched by addition of MeOH (10 mL) at 0 °C and stirring at rt for 30 min. The reaction mixture was diluted with EtOAc (150 mL) and was washed with ice-cold 1 N HCl, sat. aq. $NaHCO_3$ and brine, dried over Na_2SO_4 and evaporated. The crude material was subjected to column chromatography (90 g SiO_2, 50 mL/min flow rate, 50 mL fractions, gradient of LP/EtOAc 15% to 33%) to give the main *manno*-isomer **9a** as first eluting compound in pure form (646 mg, 54%). As second isomer the *allo*-isomer **9c** was eluted close to the last eluting *gluco*-isomer **9b** which could be isolated in a yield of 330 mg (28%, ~ 5% **9c**) which could be purified to homogeneity by trituration in MeOH (70 mg). The overall yield of isolated *manno/gluco/allo* heptenitol peracetates (**9a**−**c**) is 841 mg (70%).

Analytical data for **9a** (*manno*): R_f 0.59 (LP/EtOAc 1:1); $[\alpha]_D^{20}$ −23 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.68 (ddd, *J* = 17.2, 10.3, 7.7 Hz, 1H, H2), 5.46 (dd, *J* = 9.1, 2.4 Hz, 1H, H5), 5.37−5.32 (m, 1H, H1a), 5.30 (dd, *J* = 8.3, 2.4 Hz, 1H, H4), 5.26 (dt, *J* = 10.3, 0.9 Hz, 1H, H1b), 5.19 (app. t, *J* = 8.0 Hz, 1H, H3), 5.09 (ddd, *J* = 9.1, 5.2, 2.7 Hz, 1H, H6), 4.19 (dd, *J* = 12.5, 2.7 Hz, 1H, H7a), 4.06 (dd, *J* = 12.5, 5.3 Hz, 1H, H7b), 2.07 (s, 3H, CH_3C═O), 2.04 (s, 3H, CH_3C═O), 2.03 (s, 3H, CH_3C═O), 2.02 (s, 6H, 2 × CH_3C═O); ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.7, 169.96, 169.95, 169.7, 169.6 (5 × $CH_3\mathbf{C}$═O), 132.4 (C2), 121.1 (C1), 71.8 (C3), 69.8 (C4), 68.1 (C6), 67.5 (C5), 62.1 (C7), 21.1, 20.9, 20.82, 20.78, 20.7 (5 × $\mathbf{C}H_3C$═O); HRMS ($^+$ESI-TOF) *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{25}O_{10}$ 389.1442, found 389.1445.

Analytical data for **9b** (*gluco*): m.p.: 113.2−114.7 °C (MeOH); R_f 0.55 (LP/EtOAc 1:1); $[\alpha]_D^{20}$ −28 (*c* 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.77 (ddd, *J* = 17.1, 10.4, 6.3 Hz, 1H, H2), 5.45−5.23 (m, 5H, H1a/b, H3, H4, H5), 5.07 (ddd, *J* = 7.7, 5.6, 3.2 Hz, 1H, H6), 4.24 (dd, *J* = 12.4, 3.2 Hz, 1H, H7a), 4.07 (dd, *J* = 12.4, 5.6 Hz, 1H, H7b), 2.12 (s, 3H, CH_3C═O), 2.071 (s, 3H, CH_3C═O), 2.066 (s, 3H, CH_3C═O), 2.053 (s, 3H, CH_3C═O), 2.051 (s, 3H, CH_3C═O); ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.6, 170.0, 169.9, 169.8, 169.6 (5 × $CH_3\mathbf{C}$═O), 131.3 (C2), 120.6 (C1), 72.8, 70.7, 68.76 (C3, C4, C5), 68.64 (C6), 61.8 (C7), 21.0, 20.93, 20.86, 20.83, 20.7 (5 × $\mathbf{C}H_3C$═O); HRMS ($^+$ESI-TOF) *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{25}O_{10}$ 389.1442, found 389.1447.

L-Mannose (10). L-*manno*-Heptenitol **8a** (170 mg, 0.96 mmol) was subjected to ozonolysis (general method 1) to give L-mannose **10** as colorless oil (167 mg, 97%): R_f 0.21 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{25}$ = −6.7 (*c* 1.0, H_2O, 18h), lit.[6] −13.5 (*c* 1.0, H_2O); *Spectral data in accordance with a commercially sample of* D-*mannose (see* Supporting Information).

L-Glucose (11). L-*gluco*-Heptenitol **8b** (18 mg, 0.101 mmol) was subjected to ozonolysis (general method 1) to give L-glucose **11** as colorless oil (16 mg, 88%): R_f 0.12 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{25}$ −33 (*c* 1.0, H_2O, 18h), lit.[37](D-glucose) + 50.1 (*c* 0.7, H_2O); *Spectral data in accordance with a commercially sample of* D-*glucose (see* Supporting Information).

L-Allose (12). L-*allo*-Heptenitol (containing ~10% L-*altro*-isomer) **8c** (1.45 g, 8.15 mmol, 1.00 equiv) was subjected to ozonolysis (general method 1) to give L-allose (containing ~10% L-altrose) (1.49 g, quant.). A part of the crude material (1.00 g) was recrystallized from EtOH (2 mL) to give 0.63 g (70% recovery) of pure L-allose as white needles. **12** (L-allose): mp 132−135 °C (lit.[38] 131 °C); R_f 0.39 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{20}$ −13.7 (*c* 1.4 H_2O, 24 h) [lit.[6] $[\alpha]_D^{20}$ −10.8° (*c* 1.4, H_2O); ^{1}H NMR (400 MHz, D_2O) δ 4.86 (d, *J* = 8.2 Hz, 1H, H1), 4.14 (t, *J* = 3.1 Hz, 1H, H3), 3.85 (dd, *J* = 12.2, 2.1 Hz, 1H, H6a), 3.76 (ddd, *J* = 10.0, 5.9, 2.3 Hz, 1H, H5), 3.71−3.56 (m, 3H, H6b and H4), 3.38 (dd, *J* = 8.2, 3.0 Hz, 1H, H2); ^{13}C NMR (101 MHz, D_2O) δ 94.0 (C1), 74.2 (C5), 71.9 (C3*), 71.8 (C2*), 67.4 (C4), 61.8 (C6); HRMS ($^+$ESI-TOF) *m*/*z* [M + Na]$^+$ calcd for $C_6H_{12}NaO_6$ 203.0526, found 203.0527; *Signals marked with an asterisk could not be assigned undoubtedly. Spectral data in accordance with a commercially sample of* D-*allose (see* Supporting Information). *L-altrose was identified in the mother liquid by comparison with a commercially sample of* D-*altrose (see* Supporting Information).

4O-Acetyl-2,3O-isopropylidene-D-threose (15).[24] 4-*O*-Acetyl-2,3*O*-isopropylidene-D-threitol[24] (1.00 g, 4.90 mmol, 1.00 equiv) was dissolved in EtOAc (20 mL) in a microwave vial, IBX (4.12 g, 14.7 mmol, 3.00 equiv) was added and atmosphere was changed to argon. The vial was heated in the microwave oven (Biotage Initiator) at 120 °C for 15 min. After filtration, the filtrate was concentrated (~5 mL) and the obtained solution had to be used without further purification in the acyloxyallylation experiments (**16c**). ^{1}H NMR (400 MHz, CD_2Cl_2) δ 9.76 (d, *J* = 1.7 Hz, 1H, H1), 4.33 (dd, *J* = 11.3, 4.0 Hz, 1H, H4a), 4.30−4.26 (m, 1H, H3), 4.19 (dd, *J* = 7.0, 1.6 Hz, 1H, H2), 4.13 (dd, *J* = 11.4, 5.0 Hz, 1H, H4b), 2.07 (s, 3H, CH_3C═O), 1.48−1.46 (m, 3H, $C(\mathbf{C}H_3)_2$), 1.42−1.40 (m, 3H, $C(\mathbf{C}H_3)_2$); ^{13}C NMR (101 MHz, CD_2Cl_2) δ 200.6 (C1), 170.4 ($CH_3\mathbf{C}$═O), 111.9 ($\mathbf{C}(CH_3)_2$), 81.8 (C2), 74.8 (C3), 63.6 (C4), 26.5 ($C(\mathbf{C}H_3)_2$), 26.0 ($C(\mathbf{C}H_3)_2$), 20.5 ($\mathbf{C}H_3C$═O). Spectral data in accordance with literature.

1,2-Dideoxy-D-gulo-hept-1-enitol (16a). D-*Gulo* pentaacetate **17a** (0.71 g, 1.82 mmol, 1.00 equiv, containing ~10% D-*talo*-isomer **17c** was dissolved in dry MeOH (20 mL) and NaOMe (10 mg, 0.18 mmol, 0.10 equiv) was added. The reaction mixture was stirred at rt for 20 min, when TLC analysis showed complete conversion to a more polar spot (LP/EtOAc 3:1; DCM/MeOH 4:1). The reaction mixture was neutralized with Dowex-H$^+$ resin and filtered. Evaporation of the solvent gave the target compound **16a** as a colorless oil (330 mg, quant., containing ~10% D-*talo*-isomer **16c**): R_f 0.26 ($CHCl_3$/MeOH/H_2O 14:6:1); ^{1}H NMR (400 MHz, MeOD) δ 6.03 (ddd, *J* = 17.3, 10.6, 5.9 Hz, 1H, H2), 5.33 (dt, *J* = 17.3, 1.7 Hz, 1H, H1a), 5.19 (ddd, *J* = 10.5, 2.0, 1.3 Hz, 1H, H1b), 4.17 (ddt, *J* = 7.2, 5.9, 1.4 Hz, 1H, H3), 3.85 (dd, *J* = 4.4, 2.6 Hz, 1H, H5), 3.75 (dt, *J* = 6.1, 4.6 Hz, 1H, H6), 3.67 (dd, *J* = 11.2, 4.8 Hz, 1H, H7a), 3.59 (dd, *J* = 11.2, 6.1 Hz, 1H, H7b), 3.53 (dd, *J* = 7.0, 2.6 Hz, 1H, H4); ^{13}C NMR (101 MHz, MeOD) δ 139.9 (C2), 116.3 (C1), 75.6 (C4), 74.8 (C6), 74.1 (C3), 71.0 (C5), 64.2 (C7); HRMS ($^-$ESI-TOF) *m*/*z* [M − H]$^-$ calcd for $C_7H_{13}O_5$ 177.0768, found 177.0782;

1,2-Dideoxy-D-ido-hept-1-enitol (16b). D-*Ido* pentaacetate **17b** (0.16 g, 0.41 mmol, 1.00 equiv) was dissolved in dry MeOH (10 mL) and NaOMe (2 mg, 0.04 mmol, 0.10 equiv) was added. The reaction mixture was stirred at rt for 20 min, when reaction monitoring showed complete conversion to a very polar spot (LP/EtOAc 3:1; DCM/MeOH 4:1). The reaction mixture was neutralized with Dowex-H$^+$ resin and then filtered. Evaporation of the solvent gave deacetylated enitole species **16b** as a colorless oil (72 mg, quant.): R_f 0.30 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{20}$ + 9.4 (*c* 0.7, MeOH); ^{1}H NMR (400 MHz, MeOD) δ 5.95 (ddd, *J* = 17.0, 10.5, 6.4 Hz, 1H, H2), 5.35 (dt, *J* = 17.3, 1.7 Hz, 1H, H1a), 5.19 (ddd, *J* = 10.5, 1.8, 1.3 Hz, 1H, H1b), 4.24 (td, *J* = 6.3, 5.6, 1.3 Hz, 2H, H3), 3.78 (dt, *J* = 6.2, 4.5 Hz, 1H, H6), 3.69 (t, *J* = 3.8 Hz, 1H, H5), 3.66 (dd, *J* = 11.3, 4.8 Hz, 1H, H7a), 3.61 (dd, *J* = 11.3, 6.1 Hz, 1H, H7b), 3.57 (dd, *J* = 5.5, 3.6 Hz, 1H, H4); ^{13}C NMR (101 MHz, MeOD) δ 139.2 (C2), 116.9 (C1), 75.8 (C4), 74.6 (C3), 74.0 (C6), 72.0 (C5), 64.2 (C7); HRMS ($^-$ESI-TOF) *m*/*z* [M − H]$^-$ calcd for $C_7H_{13}O_5$ 177.0768, found 177.0777;

1,2-Dideoxy-D-talo-hept-1-enitol (16c). Dry Ethanol (40 mL) was heated to 45 °C in a round-bottom flask. In immediate succession, indium (2.25 g, 19.6 mmol, 4.00 equiv), freshly distilled bromopropenyl acetate **3a** (5.26 g, 29.41 mmol, 6.00 equiv) and subsequently crude aldehyde **15** (<4.9 mmol, as a solution in little EtOAc) were added in one portion and the mixture was stirred at 45 °C. TLC analysis (LP/EtOAc 1:1) showed complete conversion of starting material to a more apolar spot (staining blue; starting material yellow) after 30 min. The reaction was filtered and the filtrate was evaporated, leaving a white residue, which was taken up in pyridine (2.37 mL, 29.4 mmol, 6 equiv), treated with Ac_2O (1.50 mL, 14.7 mmol, 18 equiv) and stirred at rt. After 30 min, DMAP (6 mg, 0.05 mmol, 0.01 equiv) was added and it was stirred overnight at rt, when TLC analysis (PE/EA 1:1) indicated complete conversion. The reaction mixture was immersed into an ice-bath and MeOH (5 mL) was added and the reaction mixture

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

was stirred for ten min, before it was diluted with EtOAc (200 mL) and washed with ice-cold 1 N HCl, water, sat. aq. $NaHCO_3$, brine and dried over $NaSO_4$. Solvent was evaporated and the residue was taken up in dry MeOH (40 mL) and NaOMe (2 mg, 0.04 mmol, 0.10 equiv) was added. The reaction mixture was stirred at rt for 20 min, when reaction monitoring via TLC (LP/EtOAc 3:1; DCM/MeOH 4:1) showed complete conversion to a more polar spot. The reaction mixture was neutralized with Dowex-H^+ resin and filtered. After the solvent was evaporated, the residue was taken up in dry MeOH (40 mL), fresh Dowex-H^+ (4 g) added and stirred at rt overnight, when TLC analysis (DCM/MeOH 5:1) showed complete conversion to unprotected enitoles. The resin was filtered and solvent evaporated. A pure fraction of the main isomer, *talo*-enitole **16c** was isolated by recrystallization in dry EtOH (7 mL) as a white, highly crystalline solid (150 mg, 17%). The remaining isomers were isolated as a mixture from the mother liquid via flash column chromatography (45 g SiO_2, DCM/MeOH 6:1 → 2:1) as white solid. Overall yield of isolated enitoles **16a−d**: 550 mg, 63% (from 4-*O*-acetyl-2,3*O*-isopropylidene-D-threitol). Ratio of isomers (via ^1H NMR): *talo* (**16c**) 394 mg (72%), *galacto* (**16d**) 116 mg (21%), *gulo* (**16a**) 29 mg (5%), *ido* (**16b**) 10 mg (2%); Analytical data for **16c** (*talo*): m.p.: 146−147 °C (EtOH); R_f 0.23 (DCM/MeOH 5:1); $[\alpha]_D^{20}$ + 0.8 (*c* 1.0, MeOH); ^1H NMR (400 MHz, MeOD) δ 6.02 (ddd, *J* = 17.2, 10.5, 6.7 Hz, 1H, H2), 5.32 (ddd, *J* = 17.3, 2.1, 1.3 Hz, 1H, H1a), 5.21 (ddd, *J* = 10.5, 2.1, 1.1 Hz, 1H, H1b), 4.29 (ddt, *J* = 7.0, 4.7, 1.3 Hz, 1H, H3), 3.91 (td, *J* = 6.3, 1.7 Hz, 1H, H6), 3.70 (dd, *J* = 8.4, 4.7 Hz, 1H, H4), 3.62 (d, *J* = 6.3 Hz, 2H, H7a/b), 3.53 (dd, *J* = 8.4, 1.6 Hz, 1H, H5); ^{13}C NMR (101 MHz, MeOD) δ 138.3 (C2), 117.2 (C1), 75.4 (C3), 74.8 (C4), 72.7 (C5), 71.9 (C6), 64.7 (C7). HRMS ($^-$ESI-TOF) *m*/*z* $[M - H]^-$ calcd for $C_7H_{13}O_5$ 177.0768, found 177.0779.

*1,2-Dideoxy-D-gulo-hept-1-enitol hexaacetate (**17a**) and 1,2-Dideoxy-D-ido-hept-1-enitol hexaacetate (**17b**).* Dry Ethanol (30 mL) was heated to 45 °C in a round-bottom flask. In immediate succession, indium (0.75 g, 6.50 mmol, 2.00 equiv), freshly distilled bromopropenyl acetate **3a** (1.75 g, 9.75 mmol, 3.00 equiv) and subsequently D-threose **14** (390 mg, 3.25 mmol, 1.00 equiv) was added as a solution in a little EtOH and the mixture was stirred vigorously at 45 °C. TLC analysis (DCM/MeOH 4:1) showed complete conversion of starting material to a more apolar spot after 30 min. The reaction was filtered and the solvent evaporated, leaving a white residue, which was taken up in pyridine (5 mL, 61.9 mmol, 19 equiv), treated with Ac_2O (3.6 mL, 39.0 mmol, 12 equiv) and DMAP (4 mg, 0.03 mmol, 0.01 equiv) overnight, when TLC analysis (LP/EA 1:1) showed full conversion to more apolar spots. Excessive Ac_2O was quenched by addition of MeOH (5 mL) under ice-bath cooling before the reaction mixture was diluted with EtOAc (200 mL) and washed with ice-cold 1 N HCl, water, sat. aq. $NaHCO_3$, brine and dried over $NaSO_4$. The solvent was evaporated and the crude material was subjected to column chromatography on silica gel (90 g, LP/EtOAc 3:1 → 1:1) to give the main *gulo*-isomer **17a** as first eluting compound with little *talo*-isomer **17c** (806 mg, 64%, containing 10% D-*talo*-isomer). As third eluting compound, the *ido*-isomer **17b** was isolated as a pure (195 mg, 15%).

Analytical data for **17a** (*gulo*): R_f 0.68 (LP/EtOAc 2:1); ^1H NMR (400 MHz, $CDCl_3$) δ 5.78 (ddd, *J* = 17.2, 10.3, 8.0 Hz, 1H, H2), 5.48−5.29 (m, 4H, H1a/b, H4 and H5), 5.29−5.18 (m, 2H, H3, H6), 4.35 (dd, *J* = 12.1, 4.0 Hz, 1H, H7a), 3.96 (dd, *J* = 12.1, 6.2 Hz, 1H, H7b), 2.10 (s, 3H, $CH_3C{=}O$), 2.09 (s, 3H, $CH_3C{=}O$), 2.07 (s, 3H, $CH_3C{=}O$), 2.05 (s, 3H, $CH_3C{=}O$), 2.03 (s, 3H, $CH_3C{=}O$); ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.5, 170.3, 170.1, 169.9, 169.7 (5 × $CH_3\mathbf{C}{=}O$), 131.6 (C2), 121.7 (C1), 72.4 (C3), 70.7 (C4), 69.4 (C6), 68.7 (C5), 62.0 (C7), 21.05, 20.95, 20.9, 20.8, 20.7 (5 × $\mathbf{C}H_3C{=}O$); HRMS ($^+$ESI-TOF) *m*/*z* $[M + Na]^+$: calcd for $C_{17}H_{24}NaO_{10}$ 411.1262 found 411.1277.

17b (*ido*) (195 mg, 15%): R_f 0.55 (LP/EtOAc 2:1); $[\alpha]_D^{20}$ + 14 (*c* 1.0, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 5.75 (ddd, *J* = 16.8, 10.6, 6.1 Hz, 1H, H2), 5.43 (tt, *J* = 6.0, 1.2 Hz, 1H, H3), 5.40−5.28 (m, 3H, H1a/b and H5), 5.28−5.19 (m, 2H, H4* and H6*), 4.31 (dd, *J* = 12.1, 4.1 Hz, 1H, H7a), 4.03 (dd, *J* = 12.1, 5.8 Hz, 1H, H7b), 2.098 (s, 3H, $CH_3C{=}O$), 2.095 (s, 3H, $CH_3C{=}O$), 2.09 (s, 3H, $CH_3C{=}O$), 2.08 (s, 3H, $CH_3C{=}O$), 2.05 (s, 3H, $CH_3C{=}O$); ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.5, 170.05, 169.95, 169.68, 169.65 (5 × $CH_3\mathbf{C}{=}O$), 131.4 (C2), 120.1 (C1), 72.5 (C3), 71.0 (C4*), 69.6 (C6*), 68.8 (C5), 62.0 (C7), 21.0, 20.9, 20.80, 20.78, 20.75 (5 × $\mathbf{C}H_3C{=}O$); HRMS ($^+$ESI-TOF) *m*/*z* $[M + Na]^+$: calcd for $C_{17}H_{24}NaO_{10}$ 411.1262, found 411.1268. *Signals marked with an asterisk could not be assigned undoubtedly.*

*D-Gulose (**18**).* D-*gulo*-Heptenitol **16a** (300 mg, 1.69 mmol, containing ∼10% D-*talo*-isomer **16c**) was subjected to ozonolysis (general method 1) to give D-gulose **18** (300 mg, quant containing ∼10% D-talose **20**): R_f 0.28 ($CHCl_3$/MeOH/H_2O 14:6:1); ^1H NMR (400 MHz, D_2O) δ 4.89 (d, *J* = 8.4 Hz, 1H, H1), 4.07 (t, *J* = 3.5 Hz, 1H, H3), 4.00 (ddd, *J* = 6.8, 5.4, 1.4 Hz, 1H, H5), 3.83−3.80 (m, 1H, H4), 3.75 (dd, *J* = 6.2, 2.0 Hz, 2H, H6a/b), 3.63 (ddd, *J* = 8.4, 3.4, 0.5 Hz, 1H, H2); ^{13}C NMR (101 MHz, D_2O) δ 94.4 (C1), 74.4 (C5), 71.8 (C3), 70.0 (C4), 69.7 (C2), 61.6 (C6). HRMS ($^-$ESI-TOF) *m*/*z* $[M + COOH]^-$ calcd for $C_7H_{13}O_8$ 225.0616, found 225.0632; *Spectral data is in accordance with commercially available D-gulose (see Supporting Information).*

*D-Idose (**19**).* D-*ido*-Heptenitol **16b** (70 mg, 0.39 mmol) was subjected to ozonolysis (general method 1) to give D-idose **19** (70 mg, quant.): R_f 0.30 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{20}$ = +11 (*c* 0.7, H_2O, 24 h), commercial sample: + 11 (*c* 1.0, H_2O); *Spectral data is in accordance with commercially available D-idose (see Supporting Information).*

*D-Talose (**20**).* D-*talo*-Heptenitol **16c** (100 mg, 0.56 mmol) was subjected to ozonolysis (general method 1) to give D-talose **20** (100 mg, quant.): R_f 0.22 ($CHCl_3$/MeOH/H_2O 14:6:1); $[\alpha]_D^{20}$ + 19 (*c* 1.0, H_2O, 18 h), lit.[39] + 25 (*c* 1.0, H_2O); *Spectral data in accordance with a commercially sample of D-talose (see Supporting Information).*

*D-Talose (**20**) and D-Galactose (**21**).* A mixture of D-*talo*-heptenitol **16c** and D-*galacto*-heptenitol **16d** (8:2, 60 mg, 0.34 mmol) was subjected to ozonolysis (general method 1) to give a mixture of D-talose **20** and D-galactose **21** (61 mg, quant.): R_f 0.22 ($CHCl_3$/MeOH/H_2O 14:6:1); *Spectral data in accordance with a commercially sample of D-talose and D-galactose (see Supporting Information).*

*3-Iodoprop-1-en-1-yl pivalate (**22**).* Chloropropenyl pivalate[32] (2.00 g, 11.3 mmol, 1.00 equiv) was dissolved in acetone (4 mL) and added to a stirred solution of NaI (3.40g, 22.6 mmol, 2.00 equiv) in acetone (20 mL). A strong exotherm was observed at the beginning of the addition and the solution turned yellow. Further addition was done under water bath cooling. The reaction mixture was stirred at rt and under exclusion of light. After 1 h a small sample was diluted with Et_2O, washed with water and brine, dried over Na_2SO_4 and was evaporated to and analyzed by ^1H NMR to confirm full conversion to the target compound. The reaction mixture was poured into Et_2O (∼100 mL) and the white precipitate was filtered and washed with fresh Et_2O. The filtrate was washed with water, brine, dried over Na_2SO_4 and evaporated to leave a crude material (2.7 g, 89%) as a red liquid, according to ^1H and ^{13}C NMR the target compound **22** in sufficient purity to be subjected to the acyloxyallylation experiments without prolonged storage. ratio of *E*/*Z* 1:2; (*E*)-isomer ^1H NMR (400 MHz, $CDCl_3$) δ 7.41 (dt, *J* = 12.3, 1.0 Hz, 1H, =CH−O), 5.76 (dt, *J* = 12.3, 8.7 Hz, 1H, =C**H**−CH_2), 3.90 (dd, *J* = 8.7, 1.0 Hz, 2H, CH_2−I), 1.23 (s, 9H, C(**C**H_3)$_3$); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.2 (C=O), 138.4 (=CH−O) 112.9 (=**C**H−CH_2), 38.9 (**C**$(CH_3)_3$), 27.0 (C(**C**H_3)$_3$), 0.7 (CH_2−I). (*Z*)-isomer: ^1H NMR (400 MHz, $CDCl_3$) δ 7.11 (d, *J* = 6.1 Hz, 1H, =CH−O), 5.29 (td, *J* = 8.7, 6.1 Hz, 1H, =C**H**−CH_2), 3.96 (dd, *J* = 8.7, 0.7 Hz, 2H, CH_2−I), 1.30 (s, 9H, C$(CH_3)_3$); ^{13}C NMR (101 MHz, $CDCl_3$) δ 174.7 (C=O), 137.3 (=CH−O), 111.1 (=**C**H−CH_2), 39.3 (**C**$(CH_3)_3$), 27.2 (C(**C**H_3)$_3$), −4.7 (CH_2−I).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.7b03063.

Details of the quantification of the enitol ratios **16a−d** and **17a−d** via ^1H NMR. Detailed investigation of the fate of reagents **3a** and **23** under the reaction conditions. ^1H NMR and ^{13}C NMR spectra for known and new

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659

compounds (**3c−d**, **6−7**, **8a−c**, **9a−b**, **15**, **16a−d**, **17a−b**, and **22**) and comparisons of ^{1}H NMR and ^{13}C NMR spectra of synthesized and commercial samples of compounds **10−13** and **18−21** (PDF)

AUTHOR INFORMATION

Corresponding Author

*E-mail: christian.stanetty@tuwien.ac.at.

ORCID

Markus Draskovits: 0000-0002-2835-1692
Christian Stanetty: 0000-0001-7692-6932
Ian R. Baxendale: 0000-0003-1297-1552

Notes

The authors declare no competing financial interest.

DEDICATION

Dedicated to the memory of Prof. Walther Schmid.

ACKNOWLEDGMENTS

We thank the Austrian Science Fund FWF for financial support (Grants: J 3449-N28).

REFERENCES

(1) Boons, G.-J. H. K. J. *Organic Synthesis with Carbohydrates*; Wiley-Blackwell, 2000.
(2) Collins, P.; Ferrier, R. *Monosaccharides: Their Chemistry and Their Roles in Natural Products*; Wiley, 1995.
(3) Szekrenyi, A.; Garrabou, X.; Parella, T.; Joglar, J.; Bujons, J.; Clapés, P. *Nat. Chem.* **2015**, *7*, 724.
(4) Stallforth, P.; Lepenies, B.; Adibekian, A.; Seeberger, P. H. *J. Med. Chem.* **2009**, *52*, 5561.
(5) Northrup, A. B.; MacMillan, D. W. C. *Science* **2004**, *305*, 1752.
(6) Ko, S. Y.; Lee, A. W. M.; Masamune, S.; Reed, L. A., III; Barry Sharpless, K.; Walker, F. J. *Tetrahedron* **1990**, *46*, 245.
(7) Lombardo, M.; Licciulli, S.; Trombini, C. *Pure Appl. Chem.* **2004**, *76*, 657.
(8) Lombardo, M.; Gianotti, K.; Licciulli, S.; Trombini, C. *Tetrahedron* **2004**, *60*, 11725.
(9) Lombardo, M.; Morganti, S.; Trombini, C. *J. Org. Chem.* **2003**, *68*, 997.
(10) Gao, Y.; Wang, X.; Sun, L.; Xie, L.; Xu, X. *Org. Biomol. Chem.* **2012**, *10*, 3991.
(11) Lombardo, M.; Trombini, C. *Chem. Rev.* **2007**, *107*, 3843.
(12) Monrad, R. N.; Madsen, R. *Tetrahedron* **2011**, *67*, 8825.
(13) Palmelund, A.; Madsen, R. *J. Org. Chem.* **2005**, *70*, 8248.
(14) Stanetty, C.; Baxendale, I. R. *Eur. J. Org. Chem.* **2015**, *2015*, 2718.
(15) Akaike, H.; Horie, H.; Kato, K.; Akita, H. *Tetrahedron: Asymmetry* **2008**, *19*, 1100.
(16) Monrad, R. N.; Fanefjord, M.; Hansen, F. G.; Jensen, N. M. E.; Madsen, R. *Eur. J. Org. Chem.* **2009**, *2009*, 396.
(17) Binder, W. H.; Prenner, R. H.; Schmid, W. *Tetrahedron* **1994**, *50*, 749.
(18) Hyldtoft, L.; Madsen, R. *J. Am. Chem. Soc.* **2000**, *122*, 8444.
(19) Zhang, F.; Liu, Y.; Xie, L.; Xu, X. *RSC Adv.* **2014**, *4*, 17218.
(20) Banchet-Cadeddu, A.; Martinez, A.; Guillarme, S.; Parietti, V.; Monneaux, F.; Hénon, E.; Renault, J.-H.; Nuzillard, J.-M.; Haudrechy, A. *Bioorg. Med. Chem. Lett.* **2011**, *21*, 2510.
(21) Yadav, J. S.; Rao, R. N.; Somaiah, R.; Harikrishna, V.; Reddy, B. V. S. *Helv. Chim. Acta* **2010**, *93*, 1362.
(22) Schiaffo, C. E.; Dussault, P. H. *J. Org. Chem.* **2008**, *73*, 4688.
(23) Becker, M.; Liebner, F.; Rosenau, T.; Potthast, A. *Talanta* **2013**, *115*, 642.
(24) Niggemann, M.; Jelonek, A.; Biber, N.; Wuchrer, M.; Plietker, B. *J. Org. Chem.* **2008**, *73*, 7028.
(25) It is noteworthy that, for the conversion of the corresponding primary alcohol to aldehyde **15**, from a variety of oxidation conditions only a protocol with IBX in EtOAc was found applicable for our purpose as it required only filtration and concentration which prevented the decomposition of very labile aldehyde **15** otherwise observed.
(26) Due to insufficient resolution at the GC-level, quantification was based on the ^{1}H-NMRs (allylic proton) of crude enitol mixtures which were obtained from separate small scale experiments processed by a passage over a short bed of SiO_2 and collection of all entitol fractions.
(27) Lombardo, M.; Girotti, R.; Morganti, S.; Trombini, C. *Org. Lett.* **2001**, *3*, 2981.
(28) Bottoni, A.; Lombardo, M.; Miscione, G. P.; Pujol Algue, J. B.; Trombini, C. *J. Org. Chem.* **2008**, *73*, 418.
(29) Geurts, K.; Fletcher, S. P.; Feringa, B. L. *J. Am. Chem. Soc.* **2006**, *128*, 15572.
(30) Similar observations are hinted at in the original study (Palmelund 2005) as some of the investigated hexoses required a more finely dispersed quality of indium—increasing the surface and tentatively the initial rate of organyl formation—to achieve clean and full conversion which was reported to be unsuccessful with standard indium quality at prolonged reaction times.
(31) Gottlieb, H. E.; Kotlyar, V.; Nudelman, A. *J. Org. Chem.* **1997**, *62*, 7512.
(32) Bottoni, A.; Lombardo, M.; Miscione, G. P.; Pujol Algué, J. B.; Trombini, C. *J. Org. Chem.* **2008**, *73*, 418.
(33) Acyloxyallylations performed with zinc were acetylated using Ac2O in pyridine, followed by acidic aqueous workup to remove all inorganics.
(34) Matveeva, E. D.; Podrugina, T. A.; Sandakova, N. G.; Zefirov, N. S. *Russ. J. Org. Chem.* **2004**, *40*, 1469.
(35) Oldekop, Y.; Kalinina, A. *Russ. J. Gen. Chem.* **1964**, *34*, 3515.
(36) Serianni, A. S.; Barker, R. *J. Org. Chem.* **1984**, *49*, 3292.
(37) Adams, G. A.; Bishop, C. T. *J. Am. Chem. Soc.* **1956**, *78*, 2842.
(38) Redgwell, R. J.; Beever, R. E.; Bieleski, R. L.; Laracy, E. P.; Been, M. H. *Carbohydr. Res.* **1990**, *198*, 39.
(39) Jones, J. K. N.; Wall, R. A. *Can. J. Chem.* **1960**, *38*, 2290.

DOI: 10.1021/acs.joc.7b03063
J. Org. Chem. 2018, 83, 2647−2659